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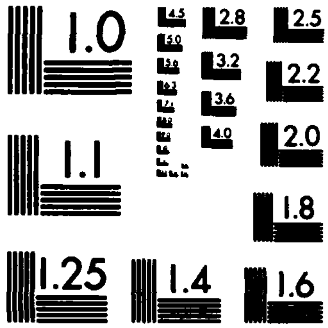
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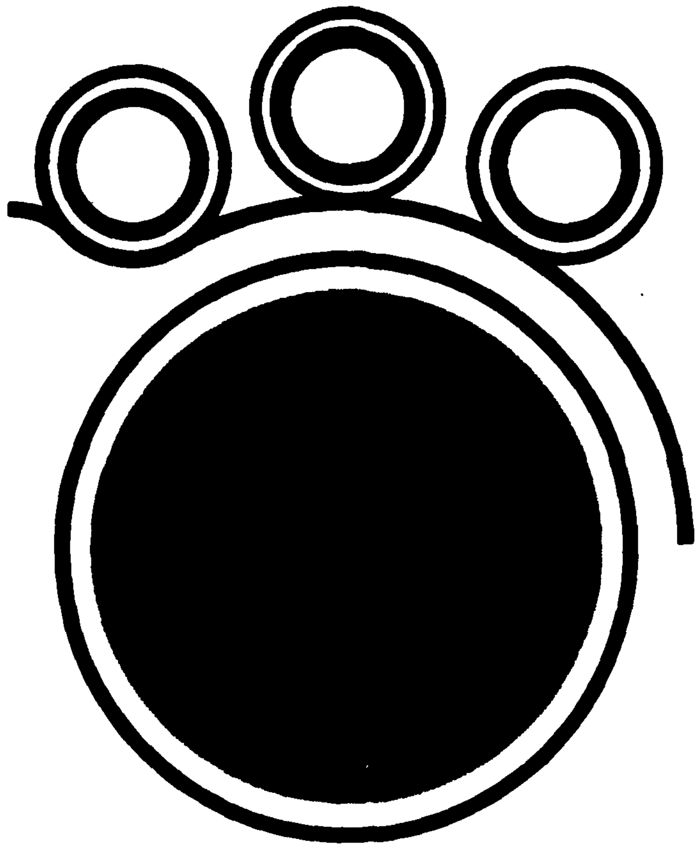
PRESS DRY CONFERENCE 1983



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U.S. Department of Agriculture, Forest Service

FOREST PRODUCTS LABORATORY

Madison, Wisconsin
September 7-9, 1983

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Press Dry Conference 1983

List of Papers

Overviews

Fundamentals

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Printed August 1983

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Overviews

OVERVIEW OF THE INSTITUTE OF PAPER CHEMISTRY PROGRAM[1]

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INTRODUCTION

The Institute of Paper Chemistry drying program comprises both funded research, performed by staff members, and academic research, performed by graduate students, with faculty supervision. The purpose of this presentation is to provide an overview of the overall Institute program. Details of particular aspects of the research have been, and will continue to be, published elsewhere.

Water removal concepts directed toward the reduction or elimination of some of the barriers to rapid, efficient drying (as exist in conventional dryers) are the primary subjects of research at the Institute. The concepts being investigated form a family, in that they are all based on the principle of high-intensity drying. High-intensity drying refers to drying under sufficiently intensive heat input conditions that the moist paper web is maintained at a temperature in excess of the ambient boiling point. Under these conditions, the vapor removal mechanism changes drastically - from the usual convective diffusion, driven by a partial pressure gradient, to a much more powerful bulk flow through and from the porous web, driven by a total pressure gradient. Thus, the drying rate tends to be limited only by the rate that heat can be supplied to the paper, and not by mass transfer effects.

The key to high-intensity drying is to improve heat transfer to the wet web. This goal is achievable through a combination of greatly increased surface temperature and considerably improved hot surface/web contact. Significantly increased temperature could be achieved by heating the dryer cylinder(s) externally, e.g., with a high-temperature burner, rather than internally with comparatively low temperature condensing steam. Smaller temperature increases could be achieved simply by using higher temperature steam. Improved contact could be achieved by considerably higher than conventional web restraining pressures (increased felt or wire tension) around the cylinder periphery and/or by a very high pressure loading (press roll or "extended nip") in the initial zone of contact between the web and cylinder.

A noteworthy alternative way of achieving high-intensity drying is to reduce the boiling point temperature, by reducing the ambient pressure in which the paper is dried. This, in turn, reduces the surface temperature required to produce rapid drying; the desirability of operating with improved contact would still remain.

In the following sections, Institute activities aimed at understanding and establishing the potential of some variations on the high-intensity principle are reviewed.

DRYING AT INCREASED SURFACE TEMPERATURE AND MECHANICAL LOADING (FABRIC TENSION)

The initial Institute work on high-intensity drying was directed toward determining how much the drying rate can be increased by operating at higher than normal surface temperatures and mechanical pressures (1,2), such that the web temperature reaches the boiling point. Pressure loadings up to about 4.3 psi (roughly 10 times those achieved by dryer fabric tension in today's dryers) and surface temperatures as much as 200°F above those currently in use were considered. Results of bench-scale experiments (involving single-side heat input) on the drying of 205 g/m^2 (linerboardlike) handsheets at these conditions showed that drying rates approximately quadruple those in typical conventional systems are possible at the maximum temperature/pressure conditions investigated. More recent tests at a pressure of about 15 psi indicated a further increase in drying rate.

The technique for measuring instantaneous heat input rate developed during these studies (2) has been incorporated into most of the other experiments to be described.

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[1]Extended abstract of a paper presented at the Press Dry Symposium [Forest Products Laboratory, Madison, WI, September 7-9, 1983].

[2]F. Ahrens and G. Kartsounes are Associate Professors, D. Wahren in Vice President-Research, S. Arenander is Visiting Researcher, Y. P. Fang, C. Devlin, J. Pounder, and S. Burton are Graduate Students, and J. Longhran is Research Assistant, The Institute of Paper Chemistry, Appleton, WI

THERMAL/VACUUM DRYING

Lehtinen (3) has reported results from an experimental investigation of a new, thermally-driven, vacuum drying process for permeable mats. Because this "thermal/vacuum" process has the potential for achieving both reduced equipment size and reduced energy use for drying, it is also being studied at the Institute. In this process, the moist mat to be dried is placed between a heater and a layer of a permeable filler material, which is in contact with a cooled wall. The temperature difference imposed across the moist mat causes the heat transfer needed to sustain rapid evaporation. Condensation occurs at the cooled wall, creating a partial vacuum with respect to the vapor pressure within the moist mat. This induces vapor flow out of the mat. The filler material serves to retain the moisture and to minimize liquid rewetting of the mat.

Because of the absence of atmospheric pressure air in the web during thermal/vaccum drying, a bulk vapor flow (i.e., high-intensity drying) condition can be achieved at low web temperatures, an advantage compared with atmospheric high-intensity drying. Furthermore, the external atmospheric pressure pushing on the paper in the vacuum zone (assuming a deformable heated or cooled wall) represents a much higher than conventional mechanical pressure loading. This yields a reduction in the thermal resistance between the heated surface and the paper web.

Bench-scale thermal/vacuum drying experiments (with single-side heating) have been performed, using 205 g/m^2 unbleached kraft handsheets, over a range of surface temperatures from 150 to 400°F and at mechanical pressures up to about 40 psi. Drying rates up to ten times greater than conventional rates have been observed. Even at surface temperatures below those typically employed in conventional dryers, drying rates up to four times conventional are indicated. Furthermore, a simplified theory of high-intensity drying developed recently suggests that if heat input to the paper is switched to the opposite side of the web after half the water has been removed, the effective drying rate will be double that found under entirely one-sided heat input. Thus, it appears that dryers only 5 to 10% of the size of today's dryers could potentially be developed using the thermal/vacuum principle. Furthermore, the fact that relatively high drying rates can be achieved at low temperature levels means that "waste heat" sources (e.g., hot condensate from other processes in the mill or lower pressure steam) could be utilized to supply the drying energy. Finally, since air-free water vapor is removed from the paper, efficient energy recovery should be possible as the vapor condenses on the cooled surface and transfers its heat to a cooler fluid.

TWO-SIDED PRESS DRYING

One of the academic projects nearing completion at the Institute is a detailed study of the heat and mass transfer aspects of two-sided press-drying (i.e., between heated wires). The experiments were performed in a hydraulic press configuration similar to that used by Byrd (4). Ten-layer unbleached 80% hardwood kraft handsheets (1650 g/m^2 basis weight) at a 45% initial moisture content were dried at various surface temperatures (290 to 430°F) and mechanical pressures (6 to 280 psi). Measurements included temperature and moisture distributions within the sheet and instantaneous caliper and heat input rate. The detailed data are being used to infer additional information, through use of appropriate mass and energy balance equations, such as contact heat transfer coefficient between the hot surface and paper web, instantaneous drying rate and sheet thermal conductivity.

It has been found that, over a significant region of the operating conditions, the drying behavior is described quite well by a simple two-zone model of high-intensity drying.

DRYING AT VERY HIGH TEMPERATURE AND MECHANICAL PRESSURE

Another of the academic projects in progress at the Institute deals with investigation of the effect of very high surface temperature (250 to 1000°F) and mechanical pressure (250 to 1000 psi) on the high-intensity drying process. The development of an instrumented hydraulic press system for this study is nearing completion. It incorporates on electrically-preheated copper plate to provide one-sided heating of the sheet.

This project will have two phases. The first will be devoted to characterizing the overall effect of operating conditions on the drying rate and on paper strength properties, using 205 g/m^2 unbleached kraft handsheets. The second phase will be directed toward quantifying the behavior of the sheet during the drying process, over a narrower range of operating conditions, in order to test hypotheses concerning the drying mechanism. Heavier (600 g/m^2 multi-ply handsheets will be used in this phase, to permit determination of the temperature, moisture and liquid flux distribution within the sheet. The instantaneous heat flux to the sheet will also be measured.

IMPULSE DRYING

The results discussed so far confirm that increasing surface temperature and mechanical pressure give improved water removal characteristics. The logical extension of these ideas would suggest the usefulness of a high temperature press roll as the basis for a dryer system. A press nip is typically operated at pressures on the order of 100 times those employed in achieving the previously described results (i.e., several hundred psi rather than a few psi). The high pressure, high heat flux water removal process occurring over a short time (much less than one second) in a hot press nip has lead to the descriptive term "impulse drying". It has been found that the rate of water removal occurring during impulse drying can be remarkably higher than in conventional drying of paper webs. The apparent reason for this desirable behavior is that mechanical removal of water, as well as evaporation, occurs as the steam generated at the hot surface passes through the sheet. An additional benefit of the heated nip results because paper becomes more compressible at elevated temperatures, which in turn leads to an enhanced wet pressing effect.

Some recently reported bench-scale experiments (5,6), and others performed as part of a student project, have helped to quantify the truly enormous water removal rates possible under impulse drying conditions. A Wahren-Zotterman wet press simulator with a heated brass surface was employed in producing the impulse. Drying rates on the order of 500 times typical conventional rates were observed, based on the moisture loss and the nip residence time! However, at the nip residence times employed (less than 20 ms), it was not possible to fully dry the sheet. Current work is being done using a small, variable speed, heated press roll to produce nip residence times from 10 to 180 ms. From preliminary data, it appears that complete drying (i.e., to ≈ 6% moisture) of fairly heavy sheets (e.g., 205 g/m^2) can be done in much less than one second in such a configuration, when high temperature (e.g., 600°F) and pressure are applied.

The student project on impulse drying, mentioned above, has included preliminary thermal energy transfer measurements. These indicate that the mechanical dewatering component of impulse drying may exceed 50% of the total water removal under some circumstances, which is very exciting from an energy use standpoint. Thus, an impulse dryer would act somewhat as an improved press section. A related benefit of the mechanical dewatering action is that the process of heat input to the press roll will be made easier by reducing the required rate of thermal energy transfer to the paper.

EFFECTS OF HIGH-INTENSITY DRYING ON PAPER PROPERTIES

Some high-intensity drying techniques have been discussed in the last few sections, from the standpoints of their desirable drying rate and energy utilization characteristics. The effects of high-intensity drying conditions on paper properties is not yet as well-quantified, but various preliminary data and observations indicate that these effects are favorable.

At the moderately high-intensity conditions corresponding to increased temperature/tension drying, it was found (1) that no appreciable change in strength properties occurred, as compared with paper dried at conventional conditions of temperature and mechanical pressure. The paper smoothness was increased.

Under thermal/vacuum conditions, Lehtinen (3) found the sheet density to increase. He also stated that improved fiber-to-fiber bonding occurred. These factors led to increased stiffness, strength and smoothness. Preliminary tests at the Institute agree with these findings. An additional Institute finding is that acceptable density and strength appear to be achievable in thermal/vacuum drying even when temperatures below conventional levels are employed. Thus, the potential for using lower-temperature (waste heat) sources would not be hampered by properties considerations.

In the impulse drying area, Arenander and Wahren (5) reported no detrimental effects on strength; preliminary tests at longer nip residence times suggest that sheet density and tensile strength are increased by impulse drying. During the student project, increased smoothness and evidence of greater conformability of the fibers to each other due to an apparent "flow" of the fiber material were noted. This latter behavior suggests that impulse drying is similar to press drying with respect to its effect on paper properties. Impulse drying might even be characterized as "very high intensity (short-time) press drying."

MATHEMATICAL MODELING OF HIGH-INTENSITY DRYING PROCESSES

To aid in understanding the various high-intensity drying processes and to develop a predictive capability, some mathematical modeling activities are also in progress at the Institute. In general, the models differ from the usual analyses of drying, mainly because the vapor movement in the web is treated as a bulk flow process (described by Darcy's law), rather than a diffusion process, and because liquid movement is considered to be influenced by not only the capillary pressure gradient but also the vapor pressure gradient.

The analyses reported so far (7,8) pertain to the thermal/vacuum drying process. However, with some alterations and extensions, it is expected that they will be capable of describing other members of the family of high-intensity drying. The impulse drying process may be more difficult to model than the others, because of the greater importance of web compression effects. A student research project is currently in progress in the modeling area.

CONCLUDING REMARKS

A major goal of research on paper drying is to enable drying processes and system(s) to be defined which offer the maximum potential economic benefit to the paper industry. Progress toward this goal can be made by identifying and developing processes which result in one or more of the following attributes:

1. Reduced dryer size and cost
2. Reduced quantity and/or quality of energy use for water removal
3. Reduced quantity and/or quality of fiber input
4. New or improved paper products.

It appears that much of the research on press drying has been motivated by factors 3 and 4, while factors 1 and 2 have given additional stimulation to the Institute research on high-intensity drying. Fortunately, there is some compatibility between those operating conditions and process strategies favorable for press drying and for high-intensity drying, so that the prospects appear to be good for achieving major breakthroughs, based on maximizing the overall potential of all four factors.

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PRESS DRYING: MEETING RESOURCE AND INDUSTRY NEEDS[1]

John W. Koning, Jr.[2]

I would also like to welcome you to the Forest Products Laboratory and Press Dry Conference 1983. I look at this Conference as a working symposium rather than a symposium as defined in the dictionary--a gathering for drinking. I suppose some of you might opt for the dictionary definition. Seriously, the prime objective of this Conference is to provide a forum for those working in the field of press drying to share their views, successes, and failures.

Thus, to set the stage, I would like to address two major topics: Resource management needs and paper industry needs. After discussing these two sets of needs I hope to show how press drying can meet them both.

Resource Needs

Many of us here have a concern for proper management of our nation's forest lands. We have in the United States, in a very broad sense, three major forested regions: The Northeast, which has primarily mixed hardwoods; the South, which has mixed softwood and hardwoods (actually 57% of the trees are hardwood); and the Northwest, which has primarily softwood. Each of these areas provides unique opportunities and problems related to proper forest management. On a national basis, however, a major concern of forest managers is what to do with our abundant, low-grade, high-density hardwoods.

These hardwoods are, to a large extent, located on dispersed lands, under private ownership, and presently unmanaged. Today, we are unable to economically manage these forests, primarily because we lack economic outlets for the poor grade material. Of course there are other problems than the lack of outlets, including the very real economic constraints of dispersed private ownership, harvesting, transportation, and processing. All of these are major concerns--as are the ecological impacts if the harvesting is done improperly. So, we find ourselves with a vast resource that is uneconomic to manage and going to waste.

Industry's Needs

The second major topic is industry's needs. Certainly one of the major needs is packaging-grade papers, a need we have historically provided for through use of long-fibered softwood pulp. This is because we require corrugated fiberboard containers to withstand the rigors of the transportation and storage environment. For example, container standards have required high tear strength, which softwood could meet.

However, in the past year a dramatic thing occurred--the approval of ASTM Performance Standard D 4169, allowing for the selection of containers that will deliver the product to the consumer with the minimum amount of packaging material. In essence, we have moved from a material specification to a performance specification. Changes in the transportation environment have modified the requirements for containers. The new standard favors containers with high compression strength. This compression requirement can be met through the use of lower valued hardwoods--provided problems of conventional papermaking and converting can be overcome, i.e., need for fully cooked pulp, refining, drainage aids, creep, scoreline cracking, etc.

Press Drying as a Solution

Press drying is a solution to these problems.

Obviously, press drying creates a major economic use for low-grade hardwoods. This makes it an effective way to help landowners fill their need to manage hardwood forest lands.

Press drying also meets industry's needs, for through press drying we are able to develop linerboard that is made from high-density hardwood fiber and has the strength properties necessary to perform as a packaging material.

Normally in research, we would be content with such a breakthrough, but press drying brings with it some other unique features that in themselves cause us to be excited. These include the use of high-yield rather than normal-yield pulps; minimal fiber refining; and a process that is less energy intensive. The latter is a major goal of many companies represented here today.

So, here we have a process that addresses many of industry's present needs:

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[1]Presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2]John W. Koning, Jr., is Assistant Director, Chemistry and Paper Research, Forest Products Laboratory, Madison, Wis.

(1) Reduced raw material costs
(2) Reduced chemical costs
(3) Increased productivity
(4) Reduced energy costs
(5) Improved product performance

I'm sure that these are some of the reasons that brought us together for this Conference.

I hope we will go away recognizing that we are on the threshold of a new process for making paper that will provide the economic outlet for large quantities of low-grade, high-density hardwoods, and thus enhance good forest management. I look forward to this Conference.

THE FUTURE OF PRESS DRYING[1]

Vance C. Setterholm[2]

Over and above all other developments now underway in the paper industry, I see the press-drying process as having distinct and unique advantages. However, we speak of press drying as if there were only one process when, in fact, there is likely to be a broad array of press-drying options, depending on the furnish used and the performance characteristics required in the finished product. Thus, by press drying, we mean to encompass a number of ways of drying not now available to the industry. This group of new technologies will produce a wide range of changes in the pulp and paper industries.

Hardwoods Substituted for Softwoods

Hardwoods will be substituted much more freely for softwoods in the manufacture of almost all paper products.

Hardwoods for Containers

High- and low-density hardwoods will be the principal raw material for the manufacture of linerboard for corrugated containers. It is possible that the strongest containers will ultimately be made from hardwoods.

Higher Drying Rates

The drying section of the paper machine of the future will be much shorter because of higher drying rates and because more water will be removed mechanically.

Higher Yields

Much higher yields of pulp from both hardwoods and softwoods will be used for almost all products. This will be a result of improved bonding made possible by press drying. Where we now produce linerboards from pulp in the 50-55% yield range, linerboard will eventually be made from hardwood and softwood pulps in the 70-90% yield range. While these products will be sufficiently stiff and strong, they may be somewhat more brittle than present products. Increased use of palletization and improved understanding of real container hazards will mitigate those potential deficiencies and make this option more feasible.

Air Forming

Dry forming or air forming will be more widely used for the manufacture of paper products. When the predicted restrictions and shortages of world water supplies become more acute, air forming will look more and more attractive. Press drying will make this new industry go.

Product Performance

Press-dried products will probably have performance characteristics superior to those of today's products. At any given moisture, container board will have higher edgewise compressive strength, higher burst strength, higher tensile strength, and better resistance to creep under load. The press-dry process will impart a higher stretch and higher tensile energy absorption.

Improved Appearance

We will realize substantially better apparent formation in printing grades. This is now only possible in laboratory handsheets made by the press-dry process.

Opacity

We will use the screen pattern to impart more reflectance and better apparent opacity to printing grades, making them equivalent to products produced by conventional drying techniques.

Structural Products from Fiber

The pulp and paper industry will move into an area of enormous potential, becoming the manufacturer of high-performance housing

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[1]Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2]Vance C. Setterholm is Project Leader, Criteria for Fiber Product Design Project, Forest Products Laboratory, Madison, Wis.

components and other structural products made from fiber.

Refining

The way the pulp is fiberized or refined will still be critical to obtaining higher performance products--even though press drying requires much less in the way of refining to prepare a pulp for papermaking. While less energy will be needed for refining, more energy will go into shive reduction.

Recycling

Press drying inevitably will increase the opportunities for recycling in this country. Whether we will reach the high levels now practiced in Japan and Europe will depend on economic considerations. But even in those countries press-drying equipment will extend the useful range of lower quality pulp.

Additives

New additives compatible with press drying will be developed so that we will achieve high-performance products even from groundwood.

Energy Conservation

Press drying will substantially lower the energy requirements per ton of product.

Environmental Concerns

Press-drying processes will have fewer environmental problems to overcome in order to maintain present water and air quality since it reduces water demands, depends more on mechanical water removal, and uses a raw material that generates fewer fines.

Geographical Impact

New mills using hardwoods will be installed in other areas of the country--even though the greatest economic advantages now lie in modification of existing mills in the southeast portion of the United States. The impact of press drying on tropical areas and underdeveloped areas of the world will be substantial when smaller scale, low-speed equipment (appropriate for those areas) is developed.

Employment

Press drying (even with small slow-speed machines) will provide employment in economically depressed hardwood areas. This is probably the most satisfying aspect of doing research in press drying.

Challenge to Machinery Manufacturers

The potential benefits I've just listed represent a sizable number of opportunities for the pulp and paper industry here and abroad. The response to this challenge will be met by the whole industry, but especially by the scientists and engineers working for a few machinery manufacturing companies.

Faced with a clear-cut need, adequate incentives, and financial support, it seems to me that these scientists and engineers will succeed. After all they wer taken from the same mold that gave the world fantastic hardware for space exploration, for harnessing atomic power, for drilling deep into the earth miles beneath the ocean surface, and for handling other challenges that, until the technology was established, were seemingly no less difficult than those now facing our industry. It not only can but will be done.

PRESS-DRYING UPDATE[1]

Vance C. Setterholm[2]

Paper companies historically have been characterized as production oriented--even though papermaking has the most sophisticated research in the forest products industry. The changes suggested by research have been implemented very slowly. There have been strong economic reasons for this slow pace, but the economic potential of press drying may change this picture dramatically. Press drying presents us with a choice--to continue to inch forward or to make progress in great strides. The pace of progress will not be decided at this meeting, but rather will be decided in the collective research and development decisions to follow this conference.

In order to give us a common background on the research leading up to this meeting, I am going to give you a brief overview of what we now know about press drying and also to suggest some areas we can build on during the Press Dry Conference 1983. In view of our diverse backgrounds, this may be sticking my neck out, but, nonetheless, I am going to say, "This is where we are, and this is what we know."

The agenda for this meeting includes talks by many of the central contributors to previous press-drying research. There are other researchers working for paper companies, machinery manufacturers, and educational institutions who, for their proprietary reasons, cannot dicuss their efforts at this time. Some of these organizations are reported to be well along in the development of concepts for commercial press-drying equipment. Their concepts have yet to be tested publicly, but their technical progress, in my opinion, is widely varied and comparable to that which will be presented at this meeting.

First, let me talk about the companies and individuals who are interested in press-drying research. The list tells a story of industry-wide excitement. There are representatives of almost all of the 50 largest pulp and paper companies in the world, representatives from 17 colleges and universities, 10 research laboratories, 18 consultants, 4 chemical companies, 16 machinery manufacturers, and 15 industry associations. Individuals and groups outside of the United States make up about 30% of every category.

A NEW KIND OF PAPER

Press drying is changing the way we perceive paper and papermaking. Most of us originally learned to be comfortable defining paper as a random matrix of fibers joined together by hydrogen bonds. Using this concept, we learned to expect paper to dissociate when soaked in water. This concept has also given us a sense of the potential strength and stiffness which can be achieved with any pulp. Our experience with some press-dried materials, however, is convincing us all that we are no longer on familiar ground. Press-dried paper often does not perform the way a conventionally made paper does. What are some of the differences we see?

1. Press-dried paper has more hydrogen bonding per unit weight of dried fiber.

2. Press-dried paper has increased levels of wet strength retention, which tells us that other bonds besides hydrogen bonds have been formed.

3. Press-dried paper gives evidence of much greater fiber conformability and flow of hemicellulose and lignin.

4. Press-dried papers, though much denser, do not show the brittle character associated with conventionally dried high-density paper.

5. Press-dried materials subjected to cyclic moisture conditions exhibit less creep deformation than conventionally dried materials subjected to the same treatment.

For these reasons, we see press drying as having the potential for producing a material not heretofore available. Clearly, this potential reflects more than the additional pressure implied in the name "Press Drying." That is, the differences we see between press-dried papers and conventional papers are more than can be accounted for by densification alone.

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[1]Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2]Vance C. Setterholm is Project Leader, Criteria for Fiber Product Design Project, Forest Products Laboratory, Madison, Wis.

WHAT WE KNOW

The term press drying refers to a large array of methods and means for drying paper. The most suitable regime or process for press drying depends heavily on the characteristics of the fiber furnish as well as the optical and physical properties desired in the finished product. Over the years, a number of key variables have been examined. Let's look at some of the key concerns and results thus far obtained.

Pulp Furnish

Pulp furnishes suitable for conventional papermaking rarely show great promise as a potential for press drying. Conventional pulps are usually low yield and well beaten compared with those prepared especially for press drying. Despite the fact that conventional pulps improve in dimensional stability and dry faster when press dried, a pulp composed of fibers already made flexible by beating generally has no need of the added pressure of press drying.

Over the years we have received samples of pulp from interested paper companies. More often than not these pulps were produced for drying by conventional means. When we made press-dried material from these pulps, it was very difficult for us to make press drying appear as attractive as it would have if we had used pulp with a higher yield and higher hemicellulose content.

Although we think of press drying in terms of high-yield pulps, the relationship between yield and press drying is more complex than we know. For example, the Forest Products Laboratory has produced kraft pulp in the 60% yield range from oak fiber which, when press dried into linerboard-weight handsheets, has a burst as high as 240 points. Other, seemingly identical, samples at the same pulp yield might have only half that strength. This difference, we believe, is caused by the manner in which the pulps are cooked and fiberized. Uniformity of chip size, uniform pulp liquor penetration, and good control of fiberizing energy are key contributors to high-quality pulp for press drying. High yield alone is not a criterion for preparing a suitable pulp for press drying.

Our studies have shown that great care must be taken in fiberizing high-yield pulps for press drying. We believe that too much energy input during refining results in the tearing apart of fiber bundles. This produces a pulp fiber far less suitable for press drying.

Densification versus Press Drying

The desire to achieve something similar to laboratory press drying with existing commercial equipment has been a compelling siren to those of us who are doing press-drying research. Most frequently, we see this type of effort being expended in the direction of attempts to densify with repeated nips. This approach seriously violates press-drying principles because it fails to control shrinkage during drying. It also inhibits the flow of hemicellulose and lignin. Of course, there is also the problem of failure to control springback. We will hear more of that during the meeting this week.

There are, of course, substantial benefits to be gained by densification, but again and again and again, we have proved to ourselves that press drying yields a substantially different set of properties than those produced by densification alone. The specific tensile strength, compression strength, and modulus of elasticity are greater for press-dried material than for conventionally dried material from the same pulp. This week we will learn more of what those differences are as well as the specific conditions required to obtain press-dried material.

Thickness Effects

The higher the basis weight of the web, the greater is the benefit obtained from press drying: Heavyweight sheets that are press dried are always more dense than conventionally dried sheets made from the same furnish. In contrast, lightweight sheets that are press dried are not much more dense than comparable sheets that are conventionally dried. In fact, press-dried sheets are sometimes lower in density than conventionally dried sheets. The opportunity of using press drying to improve products made from lightweight webs lies not in densification, but more in the areas of improving dimensional stability, in providing smoother, flatter surfaces, or improving opacity.

Hardwood-Softwood Mixtures

Handsheet studies blending high-yield, unbeaten oak pulp with low-yield beaten pine or Douglas-fir pulp have shown repeatedly that it is possible to completely substitute oak for pine without a loss of burst, tensile strength, compression strength, or modulus of elasticity provided the webs are press dried. Conventionally dried webs show a steady loss in these properties when oak is substituted for pine. Folding endurance and tear strength are substantially reduced when oak is substituted for pine in the furnish. The losses in these properties are not as great when the web is press dried as when it is conventionally dried.

Improved Creep Properties of Press-Dried Material

Press drying can substantially improve the compression-creep resistance of linerboard subjected to cyclic moisture exposure. If today's conventionally dried softwood linerboards are assumed as having "just adequate" compression-creep performance, and if the use of higher yield pulps in conventional processes reduces creep performance, producers of linerboard who wish to use higher yield pulps will need press drying or something equivalent. The ability to withstand the hazards of cyclic moisture environment is one of the outstanding virtues of press-dried materials.

Fines and Ray Parenchyma from Hardwoods

Hardwood elements rich in hemicellulose (such as ray parenchyma) bond well with fibers when press dried. This situation is in sharp contrast with conventional drying processes where ray parenchyma are considered as non-bonding material.

Density Gradients

It is not unusual to find sixfold increases in Z-direction tensile strength brought about by laboratory press drying. This past summer, Hans Anderson of the Swedish Forest Products Laboratory, working with Dr. Mark at the College of Forestry, State University of New York, measured density gradients for samples of press-dried paper prepared on the continuous press dryer at the Forest Products Laboratory. Before going back to Sweden, he called to say that his analysis showed a uniform density gradient through the thickness of the sheet. He expressed surprise because conventionally dried high-density sheets more often than not have a steep density gradient. These samples had been taken from our continuous press dryer. We believe this is one of the significant differences between densification and press drying.

CONCLUSION

So here we stand on the threshold of a new technology with enormous potential. The future will be challenging, especially for equipment manufacturers in their quest for commercialization.

Fundamentals

RAMAN MICROPROBE STUDIES OF FIBER TRANSFORMATIONS DURING PRESS DRYING

Rajai H. Atalla[2]

INTRODUCTION

The work to be described was undertaken to explore the degree to which press drying might result in changes in the states of aggregation of cellulose in pulp fibers and whether such changes are of a magnitude that might contribute to developing the distinctive desirable properties of press-dried papers. The initial incentive for the work was observation of an SEM micrograph of a press-dried sheet wherein the fibers which had been under the knuckles of the screens during drying appeared to have undergone some thermoplastic flow during the process. The question arrising was whether polymorphic change had occurred in these regions of high mechanical stress and heat flux. The Raman microprobe provided the possibility of pursuing the question in a direct manner. This report will provide an overview of the initial phases of the work.

BACKGROUND

The unique character of the bonding system developed in press drying was recognized in the early work of Setterholm and Benson (1977). Enhanced bonding has been attributed to hemicelluloses in high-yield pulps, whereas the improved creep properties and moisture resistance have been ascribed to effects of lignin in response to conditions which promote thermoplastic flow (Horn 1979 and Byrd 1970).

In all of the prior studies it has been implicit that the cellulose is relatively inert and that it is not modified in the course of press drying. The SEM micrographs suggested, however, conditions quite likely to induce polymorphic change. The challenge, therefore, was to establish whether such changes do occur.

The approach adopted was an extension of our earlier studies of polymorphic transformation in cellulose based on analysis of the Raman spectra (Atalla 1976, 1981, 1983). In order to extend our methods to analysis of press dried material, it was necessary to use the Raman microprobe which permits acquisition of spectra from microscopic domains.

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RAMAN MICROPROBE METHOD

In the Raman scattering process, light which is scattered from a sample is shifted in frequency by amounts corresponding to the molecular vibrational frequency of the sample. In Raman spectroscopy, the sample under investigation is subjected to a focused monochromatic beam, and the scattered light is analyzed to determine the variation of intensity with frequency shift. A record of the variation of intensity with frequency shift is a record of the Raman spectrum. The information contained in the Raman spectrum is, in many respects, similar to the information in an infrared spectrum, and it is complementary to it for many materials. However, particularly those materials which are optically heterogeneous, like cellulose, the Raman spectrum is more readily recorded, and it is often more informative. The Raman spectrum is quite sensitive to sample structure and to the state of molecular aggregation. In particular, we have shown it to be quite sensitive to temperature induced changes in the structure of cellulose (Atalla 1977).

The Raman microprobe is a microscope accessory to the Raman spectrometer, which makes possible aquisition of Raman spectra from microscopic domains. With respect to the present program, its key role is that it has made possible comparison of spectra from fibers in high stress zones under the knuckles of wire screens, with spectra of fibers, in the same sheet, that have not been as highly stressed.

RESULTS

Eucalyptus Pulp

The first series of experiments was carried out on a press-dried sheet prepared at the Forest Products Laboratory from a eucalyptus pulp. Raman spectra were recorded for six domains in the press-dried sheet. Three were domains that had fallen under knuckles of the wire screens during drying. The other three were domains located between the knuckle areas. Two representative spectra are shown in figure 1.

Though the spectra appear quite similar, there are meaningful differences in the relative intensities of the different spectral components, particularly in the regions between 250 and 600

cm^{-1}. The differences are brought out quite clearly in the computer resolution of the spectra into the components corresponding to different standards. The results of the three computer resolutions are shown in table 1.

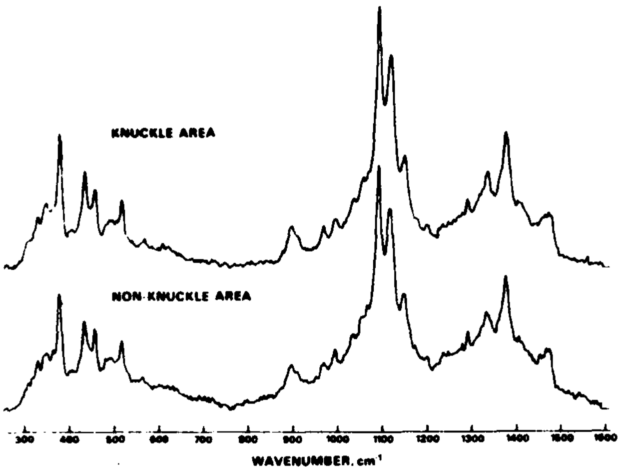

Figure 1.--Raman spectra of domains approximately 40 µm in diameter, recorded with the microprobe using the 4X objective. Knuckle spectra were from domains centered in the knuckle impression. Nonknuckle spectra were centered between knuckle impressions.

Table 1.--Conformational distributions[a] under and between knuckles of press dried eucalyptus sheet.

	Sample	k_I, %	k_{II}, %	k_O, %
Knuckle area	1	81	1	18
	2	77	1	22
	3	78	1	21
Average knuckle area		78.7	1	20.3
Nonknuckle area	4	69	1	30
	5	70	1	29
	6	68	1	31
Average nonknuckle area		69	1	30

[a]Conformational distributions based on resolution of the 250 to 550 cm^{-1} region in the spectra.

The three components k_I, k_{II}, and k_O, shown in table 1, correspond to the molecular conformations which are dominant, respectively, in celluloses I and II, and in amorphous cellulose. The data in the table indicate an average k_I content of 78.7% under the knuckles and an average of 69% elsewhere, indicating an average increase of 9.7% in k_I content as a result of dwell under the knuckles during the press drying.

The most significant implication of our observations is that the molecular mobility associated with the high temperature and moisture content during press drying can promote measurable changes in conformation and crystallinity. The observation of greater order and/or crystallinity under the knuckles represents a change that is opposite to that initially anticipated when the program was undertaken. In numerous studies we had previously observed crystallization upon exposure of pulp fibers to elevated temperatures (Atalla 1978, 1983), but the times involved had always been much longer than dwell time during press drying. We had, therefore, anticipated that the mechanical disruption of the fibers due to high pressures would be dominant. In sharp contrast, our observations indicate that the molecular mobility and the tendency to higher order and crystallinity are the dominant factors.

Oak Pulps

In an effort to clarify the role of temperature in the transformations observed, a set of handsheets press dried at different temperatures were sought. Dr. Dennis Gunderson of FPL provided us with sheets press dried with cotton fabric inserted between the sheets and the wire screens. Thus, the stress concentrations associated with the knuckles of wire screens were minimized. Two sheets were provided us, one dried at 160°F, the other at 300°F, both having been press dried for approximately 30 seconds.

In the absence of screen knuckles to bring about concentration of stress and heat flux it seemed to us wiser to record macro Raman spectra from broader domain, to provide representative average spectra. The Raman spectra were recorded with a cylindrical lens in the laser beam, so that the sampling area for the acquisition of a spectrum was approximately 1.5 mm long and varying between 10 and 25 microns wide.

The resulting spectra revealed that the crystallinity of the sample press dried at 300°F was indeed significantly higher than that press dried at 160°F. The results most closely reflecting the condition in the press dried sheets are those given in the first row in table 2. These represent the spectra accumulated over the first two scans on each sample with a total duration of approximately 90 minutes. The results indicate that the sample dried at 300°F had 67% of the k_I conformation whereas the sample dried at 160°F had only 56% k_I. The difference is a significant one, indicating greater crystallization in the sample dried at 300°F.

Another surprise in this series of results is reflected in the information acquired in subsequent scans, each set requiring an additional 90 minutes. These data clearly indicate that the cellulose in the press-dried sheets was caused to aggregate and crystallize further by the temperature elevation experienced in the laser beam. The sample originally press dried at 160°F continued to crystallize, asymptotically approaching a k_I value which appears to be somewhat higher than 66%. The sample press dried at 300°F appears to have approached an asymptote earlier and to be continuing to crystallize at a slower pace. These results clearly point to the desirability of monitoring the temperature of the sample in the laser beam. Procedures for doing so are available and will be explored in future work.

The results on the oak pulp presented in table 2 clearly support the conclusion derived from the data on the eucalyptus pulp that crystallization of the cellulosic component in the fibers can occur quite readily and to a significant and measurable extent during the short intervals used in press drying. Thus, it is clear that the molecular mobility of cellulose in the cell wall, at elevated temperatures and in the presence of moisture, is sufficient to facilitate increases in crystallinity and order in the crystalline domains in the cell walls. Perhaps more important than the suggestion of higher mobility is the implication that there is a relatively high driving force toward crystallization under the conditions encountered. Such a driving force is reminiscent of the tendency to aggregation in synthetic polymers that have been cooled rapidly from a melt. It is not uncommon, in such polymers, to observe the occurrence of crystallization and ordering in a very rapid regime. Clearly our results suggest that we need to consider the possibility that such ordering regimes occur in cellulosic fibers in the course of press drying.

Table 2.--Conformational distributions of oak pulps uniformly press dried at 160°F and 300°F.

Spectrometer scans	160°F k_I, %	160°F k_{II}, %	160°F k_O, %	300°F k_I, %	300°F k_{II}, %	300°F k_O, %
2	56	1	43	67	1	32
4	61	1	38	70	1	29
6	64	1	35	71	1	28
8	65	1	34	72	1	27
10	66	1	33	73	1	26

CONCLUSIONS

The key observations made in this work are that a measurable ordering or crystallization of cellulose occurs under press drying conditions, even though dwell times at these conditions may be relatively short. The central conclusion then is that crystallization is a very rapid process driven by a relatively high potential. A clearer definition of both process and potential must await rate measurements as well as determination of activation energy. These findings have important implications for an understanding of the mechanisms of property development in press drying. With respect to bonding, one must consider the possibility of cocrystallization of adjacent domains in the areas of contact between bonded fibers. In addition, crystallization within the fibers will likely alter their response to moisture, thus influencing the creep response of the fibers in a press-dried web.

AKNOWLEDGMENTS

The author gratefully acknowledges partial support of this work by the Forest Products Laboratory. Discussions with Dr. Vance Setterholm of FPL continue to be an integral part of this program; his collaboration is greatly appreciated.

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Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

EVALUATION OF BONDING IN PRESS DRYING AS COMPARED TO OTHER MEANS OF DENSIFYING PAPER WEBS[1]

Ernst L. Back[2]

Research on press drying of paper started at the Swedish Forest Products Research Laboratory in 1973, partly from other angles than at the U.S. Forest Products Laboratory in Madison, such as:

1. Preceeding work on the press drying of hardboard - a press-drying process invented in the U.S. in 1925 for a coarse type of TMP. In this work increasing temperature had shown a very positive effect on properties "at equal board density". Thus, press drying on liner board was stated at rather high temperatures.

2. The effect of lignin softening was considered as most important in this high temperature press drying. Work was concentrated to softwood liner pulp in the range up to 70 % yield and to TMP.

3. Single nip and 0.1 second multiple nip press drying was always compared to the effect of wet pressing at 50°C "at equal paper density".

4. All comparison thus carefully considered paper densification because of its negative effects on structural boards, on bending stiffness, on tearing resistance, and maybe on die-cutting of corrugated boards.

On this basis effects of various press drying process variables are presented, including:

a) a positive additional effect on strength only with high lignin pulps while for other pulps wet pressing to equal densification produces similar increase in strength.

b) the beneficial effects of high web temperature in press drying

c) the requirement of higher press temperatures the higher the solids content of the web entering the press drying operation

d) the low degree of delignification in hardwood parenchyma cells explains effects with parenchyma rich hardwoods

e) the advantage of momentarily restricting steam flow out of the web - thereby producing high web temperatures in continuous press drying operations.

Thereupon the following types of paper making roll nips are examined in respect to their effect on web densification and paper properties:

1. Wet pressing by press pulses in the millisecond range and from 30°C to 90°C

2. Breaker stack nips around 1 ms at 70°C and 65 % solids content - including some prolonged static pressing.

3. Machine calendering or supercalendering nips around 1.5 ms over a temperature range.

The comparison is not complete and partly covers different pulps. Also results cannot be extrapolated. But some general fingings occur. Densification in these cases is mainly a function of the maximum pressure in the press pulse, not a function of the press impulse or linear load. Hard nips thus densify more than soft ones at equal linear load. Temperatures from 30° to 90°C in wet pressing of unbleached or bleached kraft have only a negligible effect on densification but a large effect on dewatering. In prolonged nips, such as a "static" 3 minutes pressing, increasing web temperature naturally also increases densification.

Densification in wet pressing has considerable positive effects on strength properties. Densification in breaker stacks has a positive but smaller effect on strength properties. Densification in machine calendering reduces strength. High temperatures appears to be positive in any of these nips, when comparing at equal paper density.

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[1]Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2]Swedish Forest Products Researcy Laboratory, Paper Technology Department.

THE INFLUENCE OF WEB TEMPERATURE AND CONTINUOUS VERSUS INTERMITTENT RESTRAINT ON THE PROPERTIES OF PRESS-DRIED PAPER[1]

Dennis E. Gunderson[2]

The objectives of this study are to (1) develop a means of controlling web temperature and pressing variables independently during the drying process, and (2) assess the effect of web temperature and continuous versus intermittent pressing force and X-Y restraint on web densification and paperboard properties.

BACKGROUND

Web Temperatures

In the static process, internal temperature of the wet web is controlled primarily by platen temperature and vapor pressure within the wet web. Back (1) has described the mechanism in detail, and both Byrd (2) and Back (1,3) have reported wet web temperatures in excess of 150°C. High temperature is known to improve the strength and stiffness of interfiber bonds in thermo-mechanical pulps (4) and to promote the flow of hemicellulose and lignin (1,5-8) with consequent improvement in the flexibility of relatively stiff, high yield, lightly refined fibers. We suspect high temperature may cause changes in the nature of the bond as well. But wet web temperatures above 100°C can only be achieved when the pressure within the web exceeds atmospheric pressure. The web must be maintained in the pressurized state long enough for sufficient energy to transfer into the web to actually raise its temperature. If the wet web is heated above 100°C in a nip but not dried, the retained moisture may vaporize rapidly as pressure drops at the nip exit, causing internal damage to the web structure.

Pressing Force

In the static process, web densities up to 1100 kg/m^3 are achieved by the continuous application of pressing force while the web is dried from moisture contents above 40% to moisture contents below 20% (9). Pressing forces from 200 to 800 kPa yield density levels from 900-1000 kg/m^3. Much higher pressures (up to 5.5 MPa) are often used in static, laboratory experiments to create internal web pressure and thereby raise the drying temperature.

A number of concepts have been proposed for developing continuous pressing force in a dynamic process (9-12,22). They are of three general types: (1) those in which one or more metallic or synthetic fabrics are pulled taut over the curved surface of a dryer drum--producing up to 20 kPa pressing force; (2) those in which pressing force is developed as a result of a vacuum created between the hot dryer drum and a cold-impermeable belt covering the web--producing 35 kPa pressing force in the Daane design (10); and (3) Lehtinen's unique, pressurized differential temperature system (12)--with potential for producing pressing pressures greater than 60 kPa and drying temperature above 100°C. These concepts all depart significantly from present practice in the mill. Their development entails varying degrees of additional engineering effort and cost. The alternative to continuous pressure is densification by single or repetitive pressing in nips of 3-30 msec duration. Recent work has shown that moderate densification and moderate increase in strength can be achieved in low yield or blended pulps using intermittent pressing methods of more conventional design (13-15). It is important, therefore, that we evaluate the relative effectiveness of continuous versus intermittent pressing force.

X-Y Restraint

Setterholm (16) and Myers (17) have shown that restraint of X-Y shrinkage during drying increases extensional stiffness, tensile strength, and compressive strength in otherwise conventionally dried sheets. Whitsitt (18) has proposed a model in which compressive strength depends solely on in-plane stiffness and out-of-plane shear stiffness. He has verified the model with data covering a wide range of furnishes, forming and drying conditions, and densities. Restraint of shrinkage in the X-Y dimension is an integral part of the static press-dry process. It is likely that the enhanced physical properties of press-dried sheets are due, in part, to continuous X-Y restraint. In all concepts we know of, cross machine restraint depends on continuous application of pressing force. If pressing force is inter-

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[1]Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2]Dennis E. Gunderson is Research General Engineer, Forest Products Laboratory, Madison, Wis.

rupted, cross machine restraint is lost. In this study, X-Y restraint is similarly dependent on pressing force. Separation of these two parameters will require further refinement of the drying apparatus.

Density

Casey (26) characterizes density as "...probably the most important fundamental paper property. ... (influencing) every optical and physical property except sheet weight." Because of its fundamental nature he suggests it is "...the most satisfactory basis for comparing strength and other properties of different papers." In this report, comparisons which demonstrate the effect of changes in web temperature or continuous versus intermittent pressing force and X-Y restraint are presented on an equal density basis.

EXPERIMENTAL

Drying Apparatus.--The apparatus in Figure 1 was designed to provide independent control of ambient pressure and pressing force. The apparatus is comprised of a cylindrical chamber and cover; one stationary platen and one movable platen. The movable platen is secured to the cover in a manner which allows vertical travel. The movable platen acts as a sealed piston dividing the chamber into two separate volumes. Pressure in the lower chamber is set (via the two ports in the base of the cylinder) at the saturation pressure for the desired drying temperature.[3] The two platens adjacent to the web package are controlled at 25-35°C above the desired drying temperature to provide a consistent rate of heat transfer during drying in all experiments.[4] Pressing force is created by applying pneumatic pressure, in a continuous or intermittent manner, to the upper chamber via the side port in the cover. In this apparatus (as in all concepts for production press dryers I know of), X-Y restraint is derived from pressing force. Interruption of pressing results in loss of X-Y restraint. The two effects cannot be separated in the experiments reported here.

Materials.--Two different materials were used in this evaluation of press-dry process parameters. Oak furnish specimens were cut from a continuous web formed and wet pressed to 50% moisture content at 6 m/min on the FPL pilot plant machine. The furnish was 100% red oak at 60% yield, fiberized to 620-ml Canadian Standard Freeness (CSF) in a 300-mm pump-through disk refiner. Recycled handsheets were formed in a British Sheet Mold of recycled old corrugated stock obtained commercially. The stock was slushed in a hydropulper and "brushed" in the disk refiner to achieve a freeness of 550-ml CSF. The handsheets were pressed between dry blotters to 65% moisture content and then equilibrated prior to drying.

RESULTS AND DISCUSSION

Temperature Effect

The role of drying temperature in the development of press-dry properties is shown in Table 1 for the oak furnish. Two sets of results are presented. In one set, pressing force and X-Y restraint are continuous throughout the drying process; in the other set they are intermittent. The numbers in parentheses reflect the change in property resulting from an increase in drying temperature from 71° to 144°C--expressed as a percentage of the 71°C value. Properties are evaluated at equal densities: 800 kg/m^3 for intermittent restraint data; 975 kg/m^3 for continuous restraint data. For the oak furnish, burst, machine direction (MD) tensile strength, and cross machine direction (CD) tensile strength increased 20% or more at elevated drying temperatures--in both the continuous- and intermittent-restraint modes. CD compressive strength increased 14%. There was no significant change in CD extensional stiffness as a function of temperature, but the MD stiffness increased by 21-25%. Water drop absorption time was not altered by temperature in the intermittent mode, but increased by a factor of 4.9 in the continuous mode.

The recycled furnish responded similarly--but only in the continuous pressing mode. Burst, tensile strength, compressive strength, and extensional stiffness increased with temperature 22%, 18%, 13%, and 12%, respectively. In the intermittent mode, none of these properties were improved by temperature increase. Water drop absorption time was lengthened from 60 to 100 seconds by increasing temperature in the intermittent mode, but jumped from 340 to 1100 seconds in the continuous mode--a factor of 3.2. Folds were maximized for the oak fiber at 100°C drying temperature--while fold number for the recycled fiber was maximum at 71°C and declined with increasing temperature.

Tear strength for the oak furnish was essentially unchanged as a function of temperature, density, or restraint mode. Tear for the recycled fiber was reduced by increased temperature, and was reduced at the high density associated with the continuous restraint mode. As expected, tear and fold values are consistently greater for the long-fibered recycled furnish.

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[3]Temperatures from 75° to 144°C are achieved by varying the absolute pressure from 33 to 462 kPa. Moisture is continuously vented from the chamber.

[4]The use of a small temperature differential also effectively limits the wet web temperature in those cases where continuous pressing force could potentially raise the total internal pressure in the web.

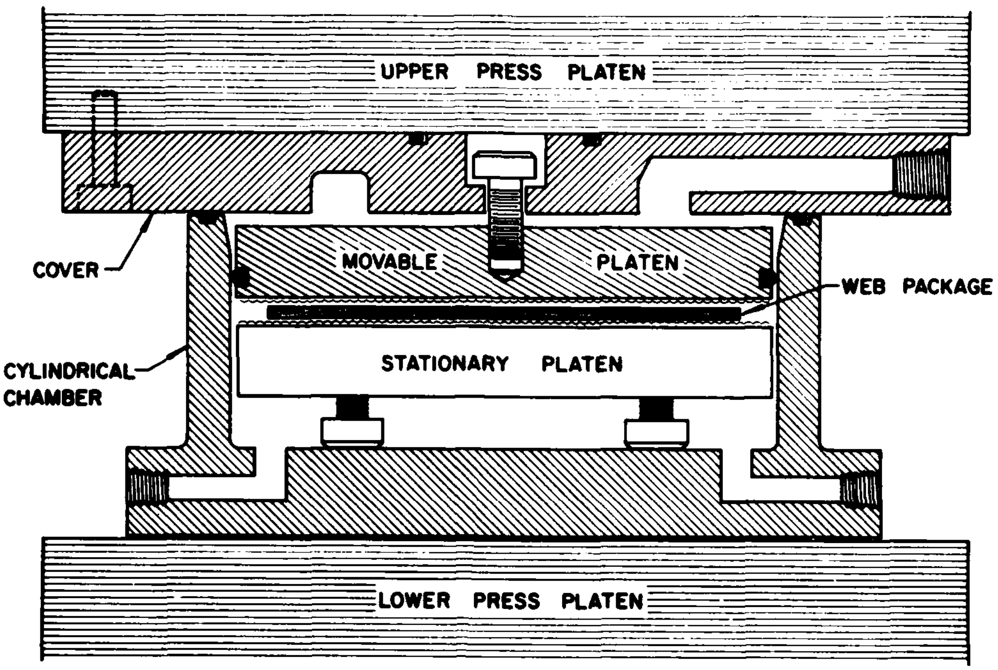

Fig. 1. Pressurized platen press. (ML83 5333)

Wet strength (tensile strength of the dried paperboard after 24-hour soak in water) was dramatically increased for both furnishes--in both continuous and intermittent pressing modes. Figure 2 shows wet strength for the recycled fiber as a function of density at four drying temperatures. It illustrates significant improvement with temperature--but relative insensitivity to density change at the lower temperatures. Results for the oak furnish were very similar.

The results of this study show that when density, pressing mode, hemicellulose content, and lignin content are fixed, wet and dry strength properties increase with drying temperature. In many respects, the moisture-resistant properties of press-dried paper are similar to those of heat-treated paper reported by Back (21) and Stenberg (20)--improved strength and dimensional stability, and reduced equilibrium moisture content. The combination of time and temperature employed in press drying is not adequate to achieve comparable levels of wet strength if applied to a dry sheet as in Stenberg's and Back's experiments. But perhaps the effect is accelerated in the presence of moisture and/or pressure. Further study of the mechanism of wet strength development is warranted, particularly because of its practical implications. If comparable qualities of moisture resistance can be obtained without embrittlement, it may be more practical to heat treat after drying than to press dry at temperatures above 100°C.

Continuous Pressing and Restraint

The most obvious effect of continuous vs. intermittent pressing and restraint is in densification. Figure 3 shows the sheet density obtained by the two modes of pressing at three pressure levels and at four web temperatures. The behavior of the recycled furnish, shown here, is characteristic of the oak furnish as well. The continuous application of pressing force leads to significantly higher density at a given pressure even though the intermittent pressing force is applied repeatedly during the drying process. At any given value of pressing force the total impulse is, of course, much greater for the continuous pressing mode. Intermittent and continuous results tend to overlap in the 850-925 kg/m^3 density region providing the opportunity for comparison at equal density of properties obtained by the two pressing methods. As pressing force increases from 200 to 800 kPa, the efficacy of added pressure declines for both continuous and intermittent processes. We observe that the relative effectiveness of continuous vs. intermittent pressing is not significantly altered by temperature increase from 71 to 144°C. On the other hand, Back has shown (19) that an increase in web temperature from 25° to 90°C reduces springback and aids densification, particularly as moisture content is reduced. These potentially conflicting views suggest the need for further study of the role of temperature in density development and,

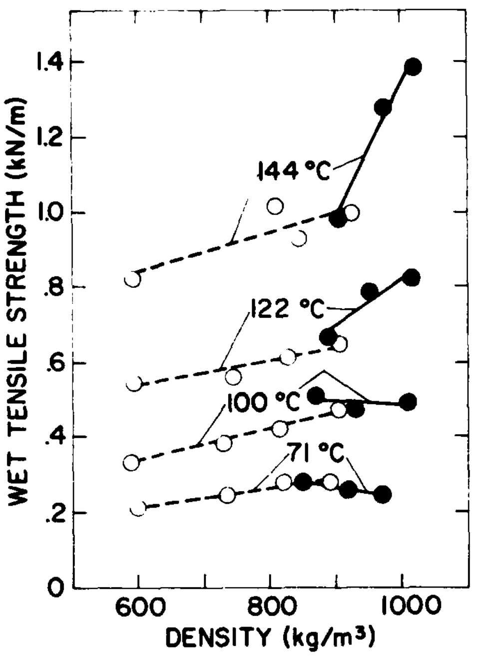

Fig. 2. Wet tensile strength after 24-hour soak in water at 22°C, as a function of sheet density and web temperature while drying. Solid lines are continuous pressing force and restraint; dash lines are intermittent. Recycled old corrugated furnish, 205 g/m² handsheets. (ML83 5332)

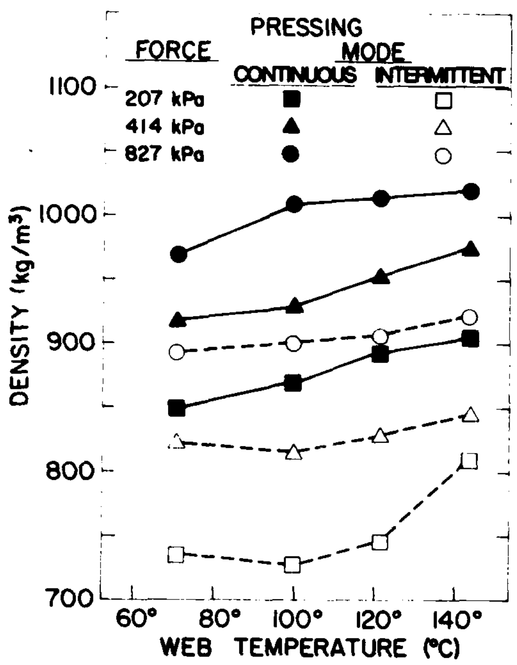

Fig. 3. Sheet density as a function of pressing force, mode, and web temperature while drying. Intermittent pressing force of 100-msec duration applied at 2-second intervals. Recycled corrugated furnish, 205 g/m² handsheets. (ML83 5334)

perhaps, better definition of the nature and role of springback. Regardless of temperature, densities greater than those shown here will require substantially higher pressing forces. Density levels associated with continuous pressing may be beyond the range attainable by practical intermittent means (3,14,15).

The effect of continuous vs. intermittent pressing force and X-Y restraint on paperboard properties is shown in Table 2. Comparisons are based on a common 100°C drying temperature and 900 kg/m³ density. Numbers in parentheses show the percentage change from intermittent to continuous restraint based on the intermittent value. The changes shown in Table 2 are a conservative measure of the difference between intermittent and continuous restraint modes because in this experiment intermittently pressed specimens are not fully unrestrained in the interval between pressing pulses. The weight of the movable platen combined with seal friction can result in a residual pressing force of 7 kPa.

For the oak furnish, continuous restraint and pressure improved every property tested except folds, tear, and water drop absorption time. Most significant improvements were in tensile strength (21%), bending stiffness (18%), burst (15%), and compressive strength (14%). The only reduction was in fold number. Strength gains due to continuous pressing were smaller for the recycled furnish; compressive strength (14%), burst (8%), and tensile (6%).

SUMMARY AND CONCLUSION

A new drying apparatus has been designed which provides control of the vapor pressure and temperature at which the web is dried and independent control of the pressing force applied to densify and restrain the web. Results show that the elevated drying temperature, continuous pressing force, and full X-Y restraint conditions of the static press-dry process play an important role in the development of press-dry properties.

Properties which tend to reflect bond strength (e.g. burst and tensile strength) improve significantly and progressively as drying temperature is increased from 71° to 144°C. Increases in drying temperature also progressively improve the tensile strength of the finished sheet when rewetted, and extend water drop absorption time under continuous-restraint pressing conditions.

Continuous restraint and pressing force are more effective in developing sheet density than are intermittent means. When pressed to equal densities and dried at 100°C, sheets continuously restrained also demonstrated better tensile and compressive strength, burst, and bending stiffness than those pressed intermittently.

Table 1. Effect of drying temperature on oak furnish (205 g/m² basis weight)[1]

Pressing force and restraint:	Intermittent restraint				Continuous restraint			
Web temperature while drying	71°C	100°C	144°C		71°C	100°C	144°C	
Property								
Density (Kg/m³)	800	800	800		975	975	975	
Burst (kpa)	503	548	[2]603	(+20)	614	765	[2]848	(+37)
Tensile strength (kN/m)	6.92	7.62	8.41	(+22)	9.1	10.2	11.3	(+24)
Tensile strain @ failure (%)	2.65	2.55	2.60	(NC)	2.5	2.82	2.38	(-5)
Extensional stiffness (kpa)	946	1006	955	(NC)	1235	1182	1296	(NC)
Compressive strength (kN/m)	3.94	4.24	4.50	(+14)	4.97	5.32	5.67	(+14)
Compressive strain @ failure (%)	0.77	0.73	0.70	(-9)	0.72	0.73	0.64	(-11)
Bending stiffness (mN-m)	2.65	2.75	3.04	(+15)	2.25	2.25	2.16	(NC)
Fold number (double folds)	37	63	39	(*)	81	154	57	(*)
Tear strength (mN)	1638	1373	1687	(NC)	1569	1520	1618	(NC)
Water drop absorption (sec)	170	80	140	(NC)	130	400	640	(+392)
Wet tensile strength (kN/m)	0.24	0.42	0.81	(+237)	0.21	0.46	1.17	(+388)
MD tensile strength (kN/m)	9.5	12.3	13.0	(+37)	12.9	15.5	17.0	(+32)
MD extensional stiffness (kN/m)	1226	1454	1537	(+25)	1515	1760	1839	(+21)

*Maximum @ 100°C. Declines at higher and lower temperatures.

[1]Results refer to cross machine direction (CD) unless otherwise specified.

[2]Numbers in parentheses reflect change from 71° to 144°C--expressed as a percentage of the 71°C value. (NC) refers to change of less than 5%.

Table 2. Continuous vs. intermittent restraint (205 g/m² basis weight)

Furnish:	Machine run oak[1]			Handsheets of recycled furnish		
Web temperature while drying:	100°C	100°C		100°C	100°C	
Pressing force and restraint:	Intermittent	Continuous		Intermittent	Continuous	
Property						
Density (Kg/m³)	900	900		900	900	
Burst (kPa)	538	[2]621	(+15)	896	[2]965	(+8)
Tensile strength (kN/m)	7.62	9.19	(+21)	12.3	13.1	(+6)
Tensile strain @ failure (%)	2.40	2.55	(+6)	2.85	3.05	(+7)
Extensional stiffness (kN/m)	963	1033	(+7)	1165	1177	(NC)
Compressive strength (kN/m)	4.34	4.96	(+14)	4.80	5.46	(+14)
Compressive strain @ failure (%)	0.72	0.78	(+8)	0.54	0.55	(NC)
Bending stiffness (mN-m)	2.16	2.55	(+18)	2.65	2.75	(NC)
Fold number (double folds)	95	50	(-47)	470	490	(NC)
Tear strength (mN)	1520	1500	(NC)	2500	2500	(NC)
Water drop absorption (sec)	50	50	(NC)	95	230	(+142)
Wet tensile strength (kN/m)	0.43	0.46	(+7)	0.46	0.49	(+6)
MD tensile strength (kN/m)	13.7	14.4	(+5)	--	--	
MD extensional stiffness (kN/m)	1594	1672	(+5)	--	--	

[1]Results refer to cross machine direction (CD) unless otherwise specified.

[2]Numbers in parentheses reflect change from Intermittent to Continuous--expressed as a percentage of the intermittent value. (NC) refers to change of less than 5%.

We conclude that press-dry properties cannot be obtained by densification alone.

The results also provide a basis from which to predict the performance of alternative processes.

RECOMMENDATIONS

Further work should refine the drying apparatus to (1) control X-Y restraint independent of pressing force, (2) provide intermittent pressing pulses at pressure levels and durations comparable to those attainable in production presses, and (3) eliminate the potential for residual restraint in the interval between pressure pulses--to the extent that it exists in the present design.

The mechanism by which high-drying temperature yields improved moisture resistance--including a comparison with heat treatment of dry paper--also seems a most interesting and potentially fruitful topic for study.

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PRESS DRYING OF THERMO-MECHANICAL PULPS[1]

K. G. Rajan, R. E. Mark, and R. W. Perkins[2]

INTRODUCTION

The application of z-direction restraint during drying, press drying, is more advantageously applied to high-yield, lightly beaten, stiff fibers than to low-yield, well-beaten fibers, since improvement in mechanical and physical properties are considerably greater for the former (1). The major objective of the present study was to consider the process feasibility and the resulting improved mechanical properties in the application of the press drying process to thermo-mechanical pulps from spruce, for the manufacture of linerboard and boxboard.

Specifically, we have made experimental determinations of the shear moduli and edgewise compressive strength (EWCS). Biot's (2) theory for buckling of a thick slab is used to predict the compressive strength of paper from its elastic properties.

While the major objective of this study was to investigate the improved mechanical properties (especially EWCS and G13), another objective was to examine press-drying from a transport phenomena viewpoint, i.e., to determine the moisture distribution as it varies with pressing time in a TAPPI mold circular sheet at different radii. The results may make possible prediction of drying stresses in paper during press-drying by adopting an approach similar to that used by Kawai (3), for example, for wood. It is also hoped that the study will facilitate improved engineering design of press-drying equipment.

RELATIONSHIP BETWEEN EWCS AND G_{13}

The edgewise compressive strength of paper may be considered to be a shear instability phenomenon and can be related to G_{13}. From Biot's theory, it is possible to use a simple approximate relation that is remarkably accurate in predicting the compressive strength over the entire range of slenderness ratios. This approximate solution is given by:

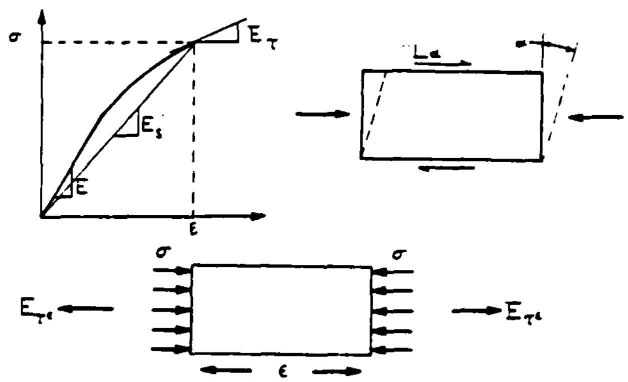

Figure 1. Definition and Significance of Various Moduli

$$\sigma_c = \frac{kL}{\frac{3}{\pi^2}\left(\frac{\ell}{h}\right)^2 \frac{kL}{E_T} + 1} \qquad (1)$$

where

σ_c = critical buckling stress,

k = a numerical factor which Biot showed to be equal to 0.91 (due to approximation in boundary conditions),

E_T and L = incremental elastic properties whose definition is provided in Fig. 1

The slenderness ratio is given by the expression $\frac{\ell}{h}$ where ℓ = free column length and h = thickness of sample.

As shown in Fig. 1, if an element of material is under compressive stress σ, and incremental stress of $E_T\varepsilon$ is needed to cause an incremental strain ε. Thus E_T can be interpreted as being the tangent modulus. Also, as shown in the figure, L represents an incremental shear modulus.

The incremental shear modulus, L, can be assumed to equal G_{13} (4). Hence, Equation 1 can be expressed as:

$$\sigma_c = \frac{k\ G_{13}}{\frac{3}{\pi^2}\left(\frac{\ell}{h}\right)^2 \frac{k\ G_{13}}{E_T} + 1} \qquad (2)$$

In the present study, no attempt has been made to obtain accurate stress-strain curves in compression. The E value in compression is assumed equal

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[1] Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

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to that obtained in tension (5,6). The E_T value is derived from the stress-strain curve itself, which can be assumed to be represented by the empirical Ramberg-Osgood relationship:

$$\varepsilon = \frac{\sigma}{E} + \beta\left(\frac{\sigma}{E}\right)^n \tag{3}$$

where E, β and n are material constants. The constants were calculated by the following procedure: From the stress-strain curve for compression, obtained by Uesaka (7):

$$\frac{E_s}{E} = 0.75 \text{ and } \frac{E_T}{E} = 0.25 \tag{4}$$

where

E_s = Secant Modulus = $\frac{\sigma}{\varepsilon}$, taken at failure in compression

From the Ramberg-Osgood relation,

$$\frac{E_s}{E} = \frac{1}{1 + \beta\left(\frac{\sigma_c}{E}\right)^{n-1}} = 0.75 \tag{5}$$

$$\frac{E_T}{E} = \frac{1}{1 + n\beta\left(\frac{\sigma_c}{E}\right)^{n-1}} = 0.25 \tag{6}$$

Solving for n and β from the above equations, we obtain n = 9 and $\beta = 1.98 \times 10^{17}$. These values were assumed to be constants for paper and were used to predict the compressive strength of the specimen material used in this study from its elastic constants by using the following equation, where E_T has been substituted from Equation 6 into Equation 2:

$$\sigma_c = \frac{k\,G_{13}}{\frac{3}{\pi^2}\left(\frac{\ell}{h}\right)^2 \frac{k\,G_{13}}{E}\left(1 + n\beta\left(\frac{\sigma_c}{E}\right)^{n-1}\right) + 1} \tag{7}$$

The above equation is an nth order equation (in σ_c) and was solved by the Newton-Raphson method.

EXPERIMENTAL

Sheetmaking

The experimental material used was commercial TMP from Norway Spruce refined to a freeness level of 440 ml CSF. The sheets were made according to TAPPI Standard T225-om800 with an initial moisture content of 68%. "TAPPI" sheets were pressed and dried in accordance with TAPPI Standard T205-om80. The pressures applied, however, were 50, 100, 150 and 200 psi (3.448×10^5, 6.895×10^5, 10.343×10^5, and 13.790×10^5 Pa, respectively) to achieve four different sheet densities. The temperature of the platen was maintained at 40°C in order to compare the TAPPI sheets with the "cold pressed" sheets described below.

"Cold pressed" sheets were simultaneously pressed and dried at 40°C to achieve density levels of the same order as those obtained with the press dried sheets. The sheets were pressed for 60 min. to a final moisture content of 5.8%. Moisture removal was facilitated by changes of dry blotters at regular time intervals.

"Press dried" sheets were prepared in a laboratory hydraulic press. The press used in this study was a Carver Laboratory Press (capacity = 20 tons or 180 kN, platen size = 200 x 200 mm). The pressures applied were 500, 100, 150, and 200 psi. Temperatures used were 115, 130, and 145°C, with drying periods of 18, 13, and 12 min., respectively, at these three temperatures.

Moisture Profile Determination

The moisture profile in the radial direction was determined at regular intervals after press-drying the samples for 10 sec. to 20 min. The press-drying was carried out at 100 psi and 130°C. The sheets were quickly removed from the platen and immediately cut into three concentric rings using a die cutter equipped with two sharp, concentric metallic rings. The inner ring had a diameter of 5.5 cm and the outer ring diameter was 11 cm. The TAPPI sheet diameter was 16 cm. Immediately after being cut, these rings were tightly sealed into preweighed plastic bags to avoid moisture loss. The combined sample plus tare weight was then recorded.

Density Measurement

Density was measured by the mercury method described by McEvoy (8). The measurement was carried out after all the mechanical tests were completed, on the assumption that thickness changes are not significant as a result of the mechanical tests.

Measurement of G_{12} and G_{13}

The torsion pendulum described by McEvoy et al (8) was used to determine the shear moduli. The experimental procedure was based on the recommendations by Uesaka et al (9). The specimen widths used were 12, 10, and 8 mm; the length of the specimen between the grips was 12 cm. These dimensions ensure that the end effect is minimized, since $\frac{W}{L} \leq 0.1$ and $W \leq 1.5$ cm. The oscillation angle was kept to within 3-5°. The axial load on the specimen was varied between 8 and 58 g (0.078-0.56 N).

In order to eliminate any effect of the longitudinal load on the torsional stiffness of the specimen, the value of the square of angular frequency (ω^2) was extrapolated to zero load by regression. The wire stiffness was also taken into account, while the air friction was neglected.

Measurement of Tensile Modulus

The strain measurement was carried out by using an LVDT device with a linear output range of $\pm$ 2mV. The testing procedure has been described by Rajan (10).

Measurement of Bending Stiffness

Bending stiffness was measured using the Taber Stiffness Tester according to TAPPI Standards; a deflection angle of 7.5° was employed.

Measurement of Edgewise Compressive Strength

The EWCS was evaluated using the Weyerhaeuser Compression tester described by Stockman (11). The specimen in this tester fails due to localized shear instability without buckling (8), a condition that makes possible true material property evaluation. The lateral spacing used was 2.5 mm for TAPPI sheets and 1.5 mm for press-dried and cold-pressed sheets, yielding a slenderness ratio of approximately 10.0, so that the EWCS measured is a true material property. The testing equipment and the testing procedure have been well described by McEvoy (8) and by Rajan (10).

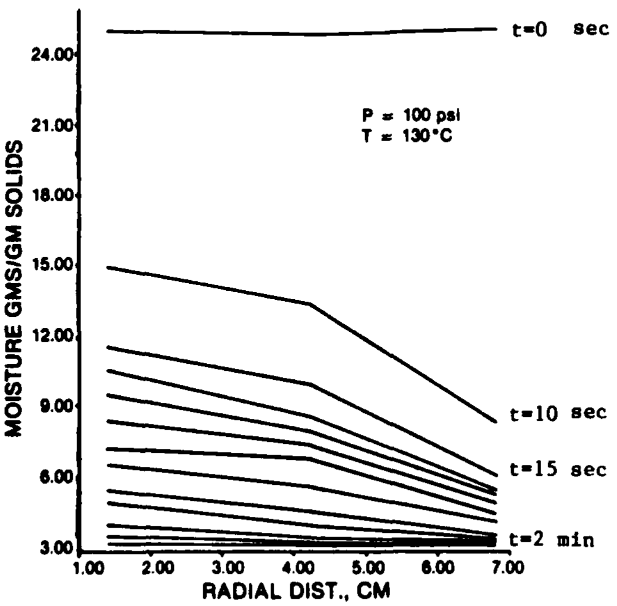

Figure 2.--Moisture Distribution During Press-Drying

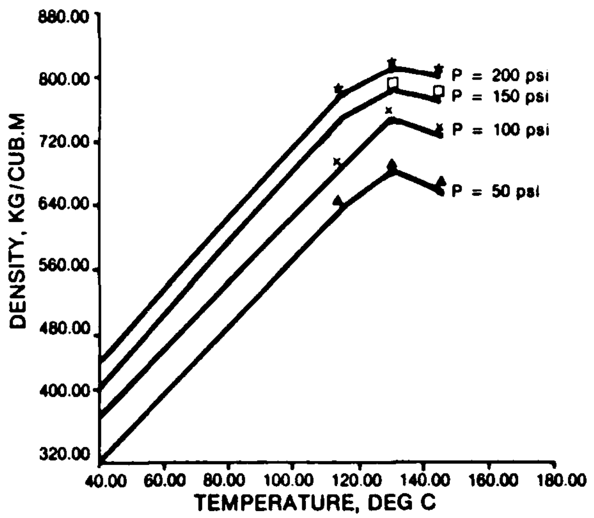

Figure 3.--Pressure-Temperature-Density Relationship

RESULTS AND DISCUSSION

Moisture Profiles

The radial moisture profiles during press drying are plotted in Fig. 2. It can be seen that the moisture content of the inner ring is 2 of 3 times higher than that of the outer ring. The largest drop in moisture takes place during the initial 10 sec. when the drying rate dropped from 7.63 to 3.58 g of moisture/g of solid/min. (10.4 lb/hr ft^2). These drying rates are considerably higher than the 2-6 lb/hr ft^2 achieved on a linerboard papermachine. The drying rate showed a further drop from 3.58 to 0.017 g of moisture/g of solid/min (0.05 lb/hr ft^2) after 14 min. These results clearly indicate that radial diffusion is an important factor in press drying of laboratory sheets. It is conceivable that the above results could be used for mathematical modeling of the pressdrying process.

Pressure-Temperature - Density Relationship

Press-drying is essentially a consolidation process. Hence, the study of density as a function of the process variables, viz., pressure and temperature, of prime importance. Results of observations on the relation of density to pressure and temperature are shown in Fig. 3. It can be seen that density increases with temperature, attains a peak at 130°C, and then drops beyond this temperature. At higher pressure this drop is lower.
One possible explanation of this observation is that as the temperature is increased, mat compaction and fiber stiffening are two competing phenomena that determine sheet density. At lower pressures and higher temperatures, fiber stiffening plays a predominant role, fiber bonding is reduced, and

therefore the density decreases beyond 130°C. At higher pressures, mat (and fiber) compaction plays a predominant role, especially during the incipient stages of drying. Hence, the density does not decrease beyond 130°C to the same extent that it does at the lower pressure.

Tensile Modulus

The tensile modulus results are plotted in Fig. 4. The E-values for TAPPI sheets and cold-pressed sheets can be fitted to the same straight line, while the E values for all press-dried sheets lie along a non-linear curve. The E values for sheets pressed at 115°C appear to fall on a slightly different curve, which may be related to the fact that the lignin softening temperature is quite close to this temperature. The E value of press-dried sheets at a given density is 32% higher, on the average, than that of cold-pressed sheets, showing clearly the potential advantage of press-drying in linerboard manufacture. One explanation that could be adduced to the improved E values is that the bonding density of press-dried sheets is higher, resulting in a higher shear transmission coefficient at the bonds. This increased bonding density may be related to the flow of lignin/and/or hemicellulose during press-drying. In Fig. 5, the tensile index values of press-dried and cold-pressed sheets are plotted. At the same density, the tensile index (or breaking length) of press-dried sheets is 11% higher than that of cold-pressed sheets.

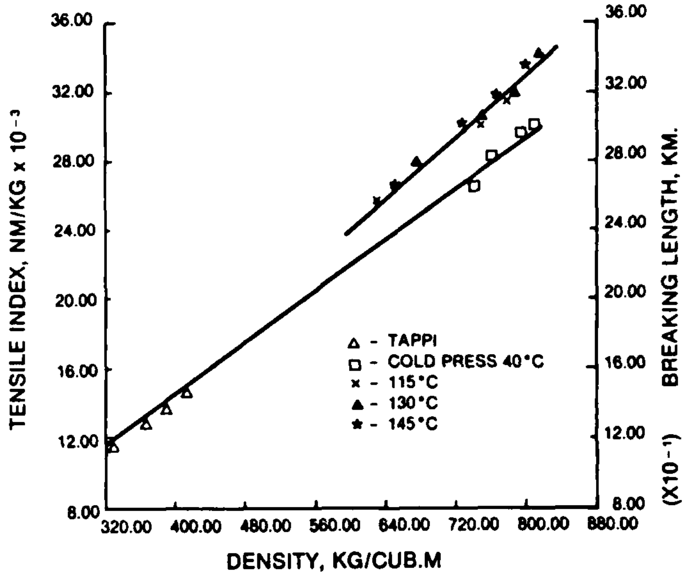

Figure 5.--Tensile Index of Press-Dried Sheets

Bending Stiffness

The results of E-bending and bending stiffness are tabulated in Table 1, from which it can be seen that press-dried sheets are 79% stiffer than cold-pressed sheets of the same density and thickness,

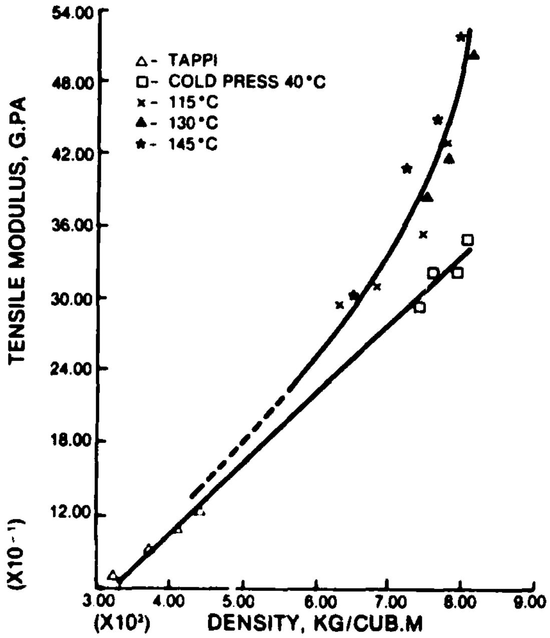

Figure 4.--Tensile Modulus of Press-Dried Sheets

Table 1. In-Plane Properties of Press Dried Sheets

Sample	ρ_{Hg} kg/m^3	$E_b\, t^3_{Hg}$ Bending Stiffness G Pa - mm^3	t_{Hg}/t_{eff}
TAPPI-50	324.8	0.3194	0.814
TAPPI-100	378.2	0.2628	0.852
TAPI-150	412.1	0.2534	0.851
TAPPI-200	445.7	0.1922	0.872
COLDPRESS-50	740.3	0.0836	0.893
COLDPRESS-100	765.2	0.0946	0.868
COLDPRESS-150	696.9	0.1104	0.816
COLDPRESS-200	811.4	0.1150	0.794
PD-115-50	635.3	0.2020	0.722
PD-115-100	686.0	0.1841	0.7658
PD-115-150	750.5	0.1560	0.744
PD-115-200	779.8	0.1434	0.817
PD-130-50	682.1	0.2537	0.646
PD-130-100	750.4	0.1838	0.727
PD-130-150	784.3	0.1615	0.739
PD-130-200	813.0	0.1497	0.799
PD-145-50	656.9	0.2701	0.626
PD-145-100	728.7	0.2384	0.691
PD-145-150	771.0	0.1781	0.713
PD-145-200	804.5	0.1721	0.758

indicating that the reduced thickness is well compensated for in press-dried sheets because of increased bonding and possibly other structural changes similar to the z-directional gradients discussed by Kimura and Mark (12).

The T_{Hg}/T_{eff} ratio, which is an indication of internal structural differences between samples, is also tabulated in Table 1. The average value for the above ratio for press-dried sheets is 13% higher than for TAPPI or cold-pressed sheets. With the use of an equation derived by Rosenthal (13), Rajan (10) has predicted that the outer surface is 35% denser than the core.

In-Plane Shear Modulus, G_{12}

The results of the measurement of G_{12} are shown in Fig. 6. The in-plane shear modulus of press-dried sheets averages 61% higher when compared to cold-pressed sheets at the same density, while, E itself is only 32% higher. This indicates the possibility of a decrease in the Poisson ratio, ν_{12}. Sheets press-dried at 115°C exhibit a transition behavior; the results for G_{12} lie along a different line. No attempt will be made here to calculate ν_{12} values, since these results are very sensitive to experimental errors in E or G_{12}.

Interlaminar Shear Modulus, G_{13}

The results of the G_{13} measurements are tabulated in Table 2 against density. The G_{13} of press-dried sheets is 82% higher than that of cold-pressed sheets, indicating the important role that temperature plays in z-directional restraint during drying. These results also confirm the previous results of McEvoy (8) and Uesaka et al (9) that G_{13} is considerably lower than previously thought.

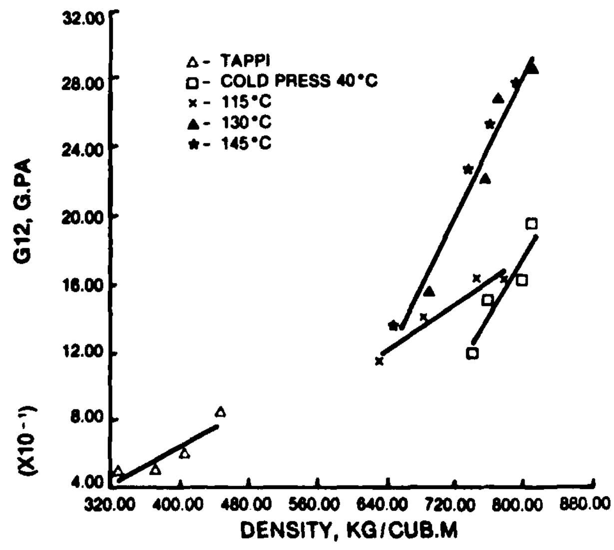

Figure 6.--In-Plane Shear Modulus of Press-Dried Sheets

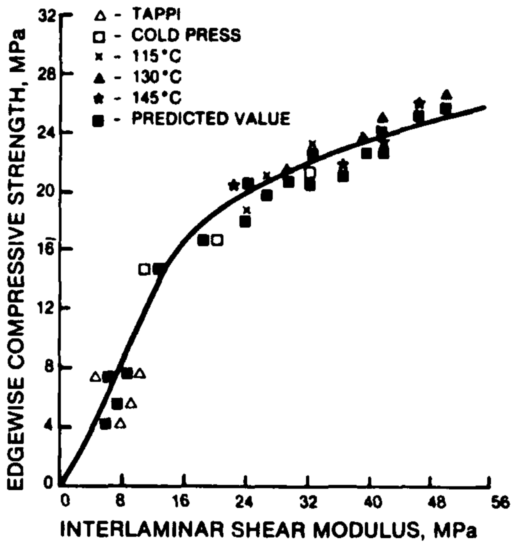

Figure 7.--Prediction of Edgewise Compressive Strength

Edgewise Compressive Strength, σ_c

The results of measurements of EWCS using the Weyerhaeuser tester are tabulated in Table 2 The press-dried sheets average 49% stronger than cold-pressed sheets sheets at a density of 740 kg/m^3 and 22% stronger than cold-pressed sheets at 810 kg/m^3. An explanation of this observation could be that at lower densities delamination of the bonds between fiber layers governs the failure mechanism, while at higher sheets densities, the mechanism is primarily one of slip-plane development. Slip-plane formation is dependent on both interlaminar bond resistance and bending resistance.

Prediction of Compressive Strength

The compressive strength of paper was predicted from Biot's theory using Equation 7 above. G_{13} and E were determined experimentally and σ_c was calculated. The results are tabulated in Table 2 and plotted in Fig. 7 against G_{13}. As explained earlier, n and β were determined from the stress-strain curve for compression obtained by Uesaka (7) ($n = 9$ and $\beta = 1.98 \times 10^{17}$.

The predicted results for critical buckling stress versus G_{13} can be seen to be in close agreement with the experimental results. The curve shown is the best fit curve for the experimental results. The experimental points are also plotted. Each point on the graph represents the average of 6 replications.

From these results, it can be concluded that at low densities (up to 400 kg/m^3) the compressive strength of paper is approximately numerically equal to the interlaminar shear modulus. At higher densities the σ_c/G_{13} ratio is less than 1.0, but nevertheless there appears to be a proportional relation between them.

The above analysis using Biot's theory includes many assumptions, such as $L = G_{13}$ (L is the incremental shear modulus), and uses the Ramberg-Osgood relationship to obtain the tangent modulus. These assumptions make this analysis partly empirical, but nevertheless the use of these relations can be justified for reasons mentioned earlier.

SUMMARY

Press-dried specimens of paper made with thermomechanical pulp have been prepared and experimentally evaluated. There appear to be several beneficial effects on sheet mechanical properties, including Youngs modulus, interlaminar shear modulus, and edgewise compressive strength of paper. Moisture profiles obtained clearly show that radial diffusion could be an important factor in the mathematical analysis of the problem.

The results also made possible the prediction of compressive strength of paper using Biot's theory for buckling of a thick slab. The predicted values agree closely with the experimental results. These results should stimulate further analytical and experimental work aimed at explaining the compressive failure mechanism of paper at the micromechanics level.

Table 2. Prediction of Compressive Strength

Sample	Hg-Density Kg/M^3	G_{13}, M Pa	(σ_c),M Pa Experimental	(σ_c),M Pa Predicted
TAPPI-50	324.8	5.88	4.95	4.86
TAPPI-100	378.2	7.18	5.54	5.44
TAPPI-150	412.1	7.01	7.49	7.36
TAPPI-200	445.7	8.25	7.96	7.82
COLDPRESS-50	740.3	13.32	15.13	14.86
COLDPRESS-100	765.2	18.40	17.62	17.31
COLDPRESS-150	796.9	29.44	21.19	20.82
COLDPRESS-200	811.4	31.81	21.30	20.94
PD-115-50	635.3	23.93	18.62	18.30
PD-115-100	686.0	26.35	20.53	20.17
PD-115-150	750.5	32.82	22.41	22.02
PD-115-200	779.8	40.12	23.29	22.90
PD-130-50	682.1	29.40	21.24	20.87
PD-130-100	750.4	39.79	23.41	23.01
PD-130-150	784.3	41.77	24.12	23.71
PD-130-200	814.0	49.69	26.14	25.72
PD-145-50	656.9	24.83	20.17	20.35
PD-145-100	728.7	36.39	21.63	21.27
PD-145-150	771.0	41.35	23.22	22.84
PD-145-200	803.5	46.80	25.44	25.04

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THE EFFECT OF PRESS-DRYING ON PAPER STRUCTURE[1]

R.S. Seth, A.J. Michell and D.H. Page[2]

Unlike the conventional drying process in papermaking where the sheet dries without any significant z-direction restraint, press-drying is a process whereby external pressure is applied to the wet web while it dries at a temperature 100°C or above. At these elevated temperatures, the fiber components are softer and the conformability of the moist sheet is enhanced leading to increased bonding and strength.

Most of the published work on press-drying has been done on sheets of high grammages. The sheets were generally dried by restraining them between sets of wire screens in heated platens. The properties of these sheets were compared with those prepared by conventional methods. It is now recognized that the press-dried sheets thus prepared are unsatisfactory. For example, being heavy in grammage, some of the physical properties such as zero-span tensile strength and light scattering coefficient cannot be reliably measured. Further, being dried between wire screens, the sheets have unduly high surface roughness, and are spot-bonded where wire knuckles compact the sheets. As a result, the bulk of the sheets is erroneously higher. Moreover, recent studies have shown that surface unevenness can adversely affect measurement of edgewise compressive strength of the sheet. Therefore, for a meaningful comparison of sheet properties, it is necessary that both press-dried and wet-pressed sheets should have similar internal structures and surface textures, and be free from defects.

After a careful consideration of various previously-used methods and porous surfaces required for rapid moisture escape, a simple method was developed for producing press-dried and wet-pressed sheets employing similar pressing surfaces. It is similar to the conventional method used for wet-pressing laboratory sheets; the sheets are press-dried between a polished steel plate and a blotter backed by a sheet of sintered metal-fiber filter. Moisture escapes readily from this arrangement (figs. 1 and 2). Conditions under which sheets of different weights, appropriate to both papers as well as paperboards, could be dried at various levels of consolidation were determined.

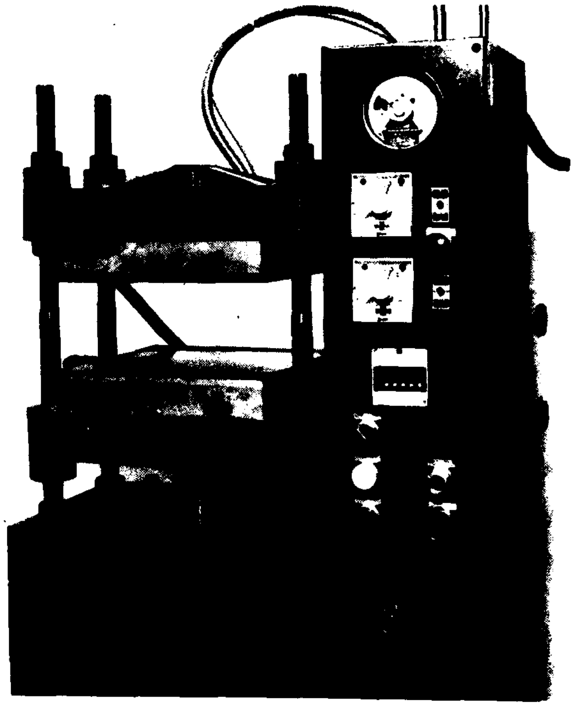

Figure 1. The photograph shows the automatically timed press, with electrically heated platens, that was used for the press-drying work.

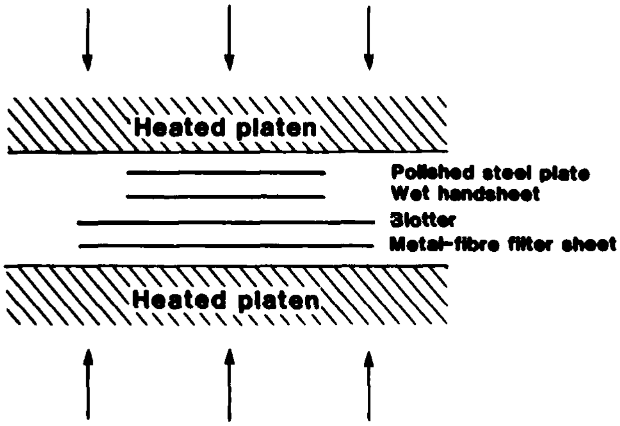

Figure 2. The schematic drawing shows the arrangement that was used for preparing press-dried sheets in the laboratory.

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[1] Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2] Pulp and Paper Research Institute of Canada, 570 St. John's Blvd., Pointe Claire, P.Q., Canada, H9R 3J9.

The effect of wet-pressing and press-drying on sheet consolidation has been studied for several pulps which cover a wide range of fiber conformabilities and yields (table 1). Two structural parameters have been used to characterize consolidation; one is apparent sheet density and the other is light scattering coefficient. Plots of apparent density against scattering coefficient are given in figure 3. If the structures of the wet-pressed and press-dried sheets are identical, the results for the two pressing methods should fall on the same curve. For the 66%-yield unbleached kraft pulp, the plots for wet-pressed and press-dried sheets are identical; for other pulps, they are similar but not identical. The difference is substantial for thermomechanical pulp. While for some pulps, the press-dried sheets have a higher density at the same scattering coefficient than the wet-pressed sheets, for others, it is the opposite; the pressing pressure also seems to have an influence. Thus, while wet-pressed and press-dried sheets that have rather similar apparent density-scattering coefficient plots may be obtained implying similar structures, some detailed differences remain which seem fundamental to the press-drying process, and will be discussed in the delivery of the paper.

Table 1. Description of pulps for which the effect of press-drying and wet-pressing on sheet consolidation was studied.

A. Laboratory-made, never-dried, unbleached kraft pulp of black spruce, 50%-yield.
B. Laboratory-made, never-dried, unbleached kraft pulp of black spruce, 66%-yield, 750 mL CSF.
C. Cotton linters, beaten for 6 x 10^3 rev in PFI mill to 270 mL CSF.
D. Commercial dried, bleached kraft pulp of softwood, beaten for 1.5 x 10^3 rev in PFI mill.
E. Commercial, never-dried, thermomechanical pulp (TMP) of black spruce, refined in two stages at 8.50 MJ/kg and 30% consistency after second stage, 177 mL CSF.
F. Commercial, never-dried, sulphonated chemimechanical pulp (SCMP) of softwood, refined in two stages at 7.15 MJ/kg and ~25% consistency, 280 mL CSF.
G. Commercial, flash-dried, bleached kraft pulp of softwood, unbeaten.
H. Laboratory-made, never-dried, unbleached bisulphite pulp of black spruce, 81%-yield, 780 mL CSF.

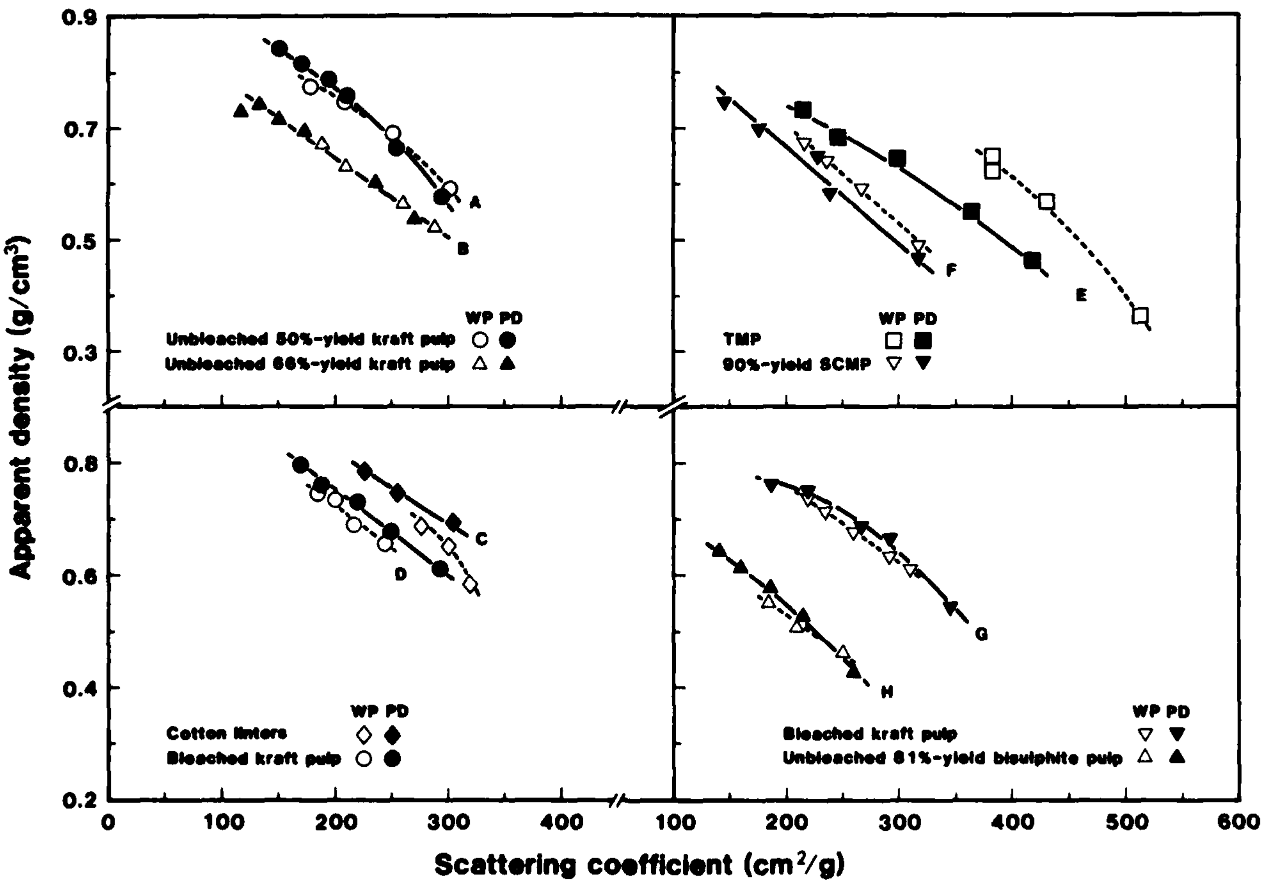

Figure 3. Plots of apparent density against scattering coefficient for sheets of various pulps wet-pressed and press-dried over a range of pressures. The apparent density was calculated from bulking caliper measurements made on five sheets. The scattering coefficient was determined at 681 nm wavelength. The latency from the mechanical and high-yield pulps was removed before sheetmaking.

PRESS-DRYING AT MIAMI UNIVERSITY[1]

Michael H. Waller[2]

INTRODUCTION

Miami University's interest in the press- drying process was strongly stimulated by Von Byrd when he presented a seminar at Miami in 1981. One Master's thesis has been completed, (Wolf,1982), and additional work is contemplated in modeling the drying process (Lee & Hinds, 1981) and in attempting to understand the press- drying mechanism. Some of Wolf's work has been reported elsewhere, (Waller & Wolf, 1982), but a summary will be presented here.

Paper made from hardwood CTMP pulp at various levels of freeness and yield was press-dried. A drying rate, physical property, and wire mesh study was conducted under various conditions of pressure, temperature, freeness and grammage. While high drying rates have been achieved, 150 $kg/m^2/hr$, drying under these conditions appears to unfavorably affect sheet physical properties. The studies were conducted at a variety of press drying conditions: pressures of 70-400 kPa; temperatures of 100-200 C; basis weights of 60-200 g/m^2; freenesses of 700-200 ml CSF, with a variety of screen mesh sizes.

EXPERIMENTAL PROCEDURE

All press- drying experiments were conducted by forming handsheets which were wet pressed to a moisture content of 60%, then sandwiched between screens and thermostatically controlled polished aluminum hot plates. The plates were held in a framework which was then loaded to the selected pressure by a hand-operated hydraulic jack. Applied pressure was read from a pressure gauge.

The CTMP pulp was obtained from the C.E. Bauer Company of Springfield, Ohio. Sugar maple was the species with the largest proportion, 31%, with poplar, red maple, white birch, yellow birch and beech each having proportions between 10 and 16%.

Drying Study

The pulp was prepared to a freeness of 500 ml CSF, from which handsheets of 200 g/m^2 were formed according to TAPPI standard T 205 om-81. 100 mesh wire screens (100x100 wires/inch) were used. Sheet moisture content was determined at 5 second intervals by interrupting drying and measuring moisture. Pressures between 70 and 350 kPa and temperatures from 100 to 200 C were used.

Wire mesh study

A 2^3 factorial design was used to study the effects that wire mesh size(50x61 - 189x64), basis weight(60-200 g/m^2) and press pressure(70-210 kPa) had on the density, breaking length, burst index and tensile index of press-dried handsheets. The sheets were dried to a moisture content of 10%.

Physical Property Evaluation

To compare press-dried with conventionally dried paper, 60 g/m^2 handsheets were prepared. The handsheets were then separated into two groups and either press-dried or placed on drying rings and conditioned according to TAPPI standards at least 24 hours before testing. The press-dried group of handsheets was dried to about 10% moisture, using 244x68 wire mesh screens.

A 2^3 factorial design was used to study the effects that CSF(700-200 ml), temperature(100-200 C), and pressure(70-400 kPa) had on the properties of density, tensile index, burst index, opacity and stiffness.

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[1] Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2] Associate Professor of Paper Science and Engineering, Miami University, Oxford, Ohio.

DISCUSSION OF RESULTS

Drying Study

Setterholm(1979) has suggested that drying rates of 150 $kg/m^2/hr$ at 177 C are possible. At St. Annes, drying rates of 80 $kg/m^2/hr$ at 110 C were obtained- Attwood(1981). These are quite high when compared with the typical drying rate of a high speed linerboard machine: 15 $kg/m^2/hr$.

Figure 1 is a plot of sheet moisture percentage versus time for three runs at 100 C with pressures from 70 to 350 kPa. Note that there is very little change in drying rate as pressure is changed with temperature being held constant. At first glance this is quite contradictory to Ahrens(1982), but the pressures here are quite high, approaching an asymptotic impact.

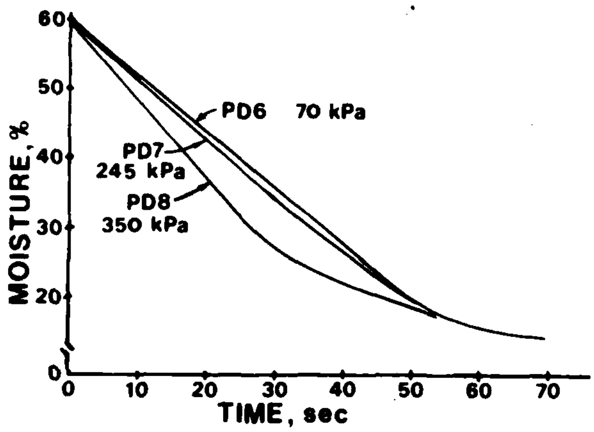

Figure 1 - Dewatering versus Time and Pressure

Figure 2 is a plot of sheet moisture percentage versus time for three runs where pressure is held constant at 70 kPa and temperature is varied from 100 to 150 C. Note the strong changes in drying. Average drying rates for drying from 60 to 6% moisture have been calculated from the data in Figure 2 and are shown in Table 1.

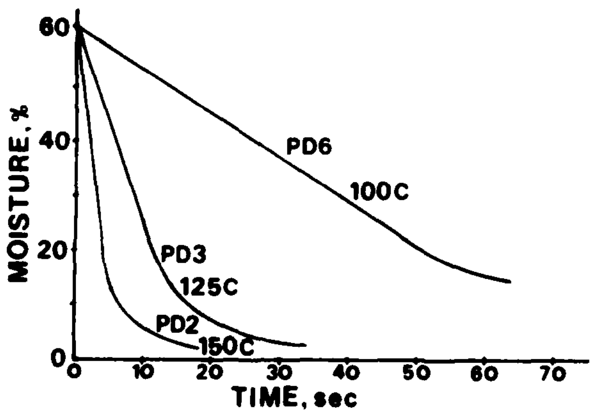

Figure 2 - Dewatering versus Time and Temperature

Table 1 - Drying rate for various temperatures

Temperature, C	100	125	150	200
Rate, $kg/m^2/hr$	14.3	57.4	154.	160.

The average rate, however, tells an incomplete story, since the usual model for drying involves a constant drying rate period followed by a falling rate. Another method of examining the data is to plot specific areal moisture, g/m^2, versus time. These plots showed that moisture was being removed at a decreasing rate through the entire drying process, without the familiar constant- and falling-rate zones of conventional drying. Accordingly, regression equations were developed which were of the general polynomial form shown in Eq. 1:

$$w = A + B1\ t + B2\ t^2 + B3\ t^3 \qquad (1)$$

Here w = specific areal water content, g/m^2
A = constant (regression intercept)
B1,B2,B3 = regression coefficients
t = time, sec

These equations, which had a multiple correlation of regression of 0.98, were then used to calculate drying rate as a function of time and specific moisture. Plots for three runs are shown in Figure 3. Note the monotonically decreasing rate as moisture is reduced. Perhaps this is due to the nature of the press drying process with continual z-direction restraint.

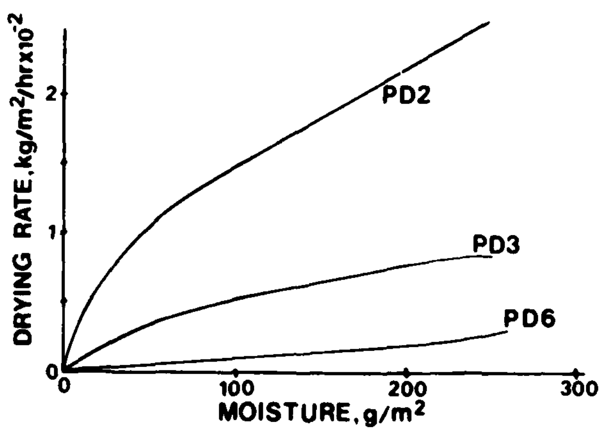

Figure 3 - Drying Rate versus Moisture and Temperature

Instantaneous drying rates at various moistures and temperatures at a constant pressure of 70 kPa are shown in Table 2.

Table 2 - Drying Rates at Typical Moistures

Temp. C	Moisture Content - g/m² 200	150	100	50
100	21	18	14	8
125	77	65	51	36
150	222	188	147	100
200	206	177	147	105

Wire Mesh Study

Preliminary experiments with a 100 mesh wire showed that a press-dried handsheet was denser than a control sheet at 200 g/m^2 but not at 60 g/m^2, as shown in Table 3.

Table 3 - Density affected by Press-Drying

Basis weight (g/m^2)	Press Pressure (kPa)	Wire Mesh (meshes/inch)	Density (g/cm^3)
60	350	Control	0.273
60	70	50x61	0.279
60	210	50x61	0.297
60	70	189x64	0.331
60	210	189x64	0.350
200	350	Control	0.423
200	70	50x61	0.474
200	210	50x61	0.510
200	70	189x64	0.512
200	210	189x64	0.622
130	140	88x91	0.503

This behavior suggested a wire mesh-basis weight/press-drying interaction. Figure 4 is a plot of density versus wire mesh size and Figure 5 is density versus basis weight. At higher basis weights, the effects of wire mesh and press pressure were more noticeable. As wire mesh increases, the effects on physical properties should approach asymptotic conditions. The mesh size/fiber length characteristic should be a controlling parameter for strength development.

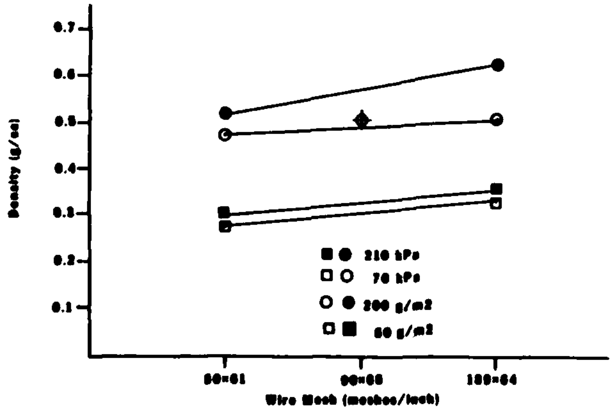

Figure 4 - Density versus Wire Mesh Size

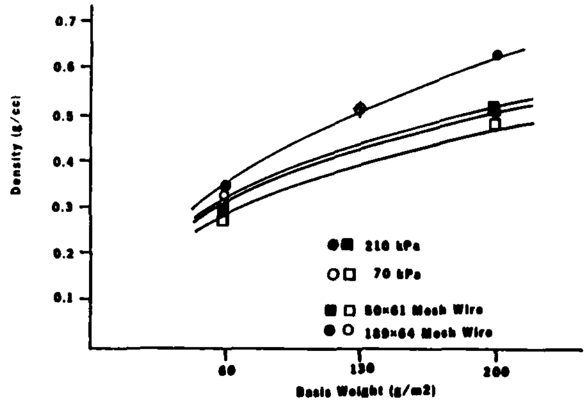

Figure 5 - Density versus Basis Weight

Figure 6 is a plot of tensile index versus wire mesh for various basis weights. Note that the effect of wire mesh is important only at high basis weights. All strength properties behaved in this fashion.

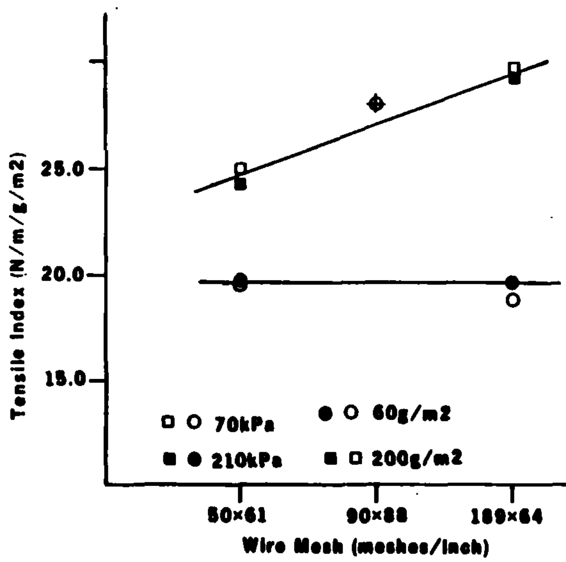

Figure 6 - Tensile Index versus Wire Mesh Size

Physical Property Evaluation

Since the fine mesh screens gave the best sheet property results, a 244x68 mesh screen was used to conduct this study. As a general indicator of strength development, tensile index is plotted versus CSF in Figure 7. Here 81% yield press-dried pulps are compared to control handsheets. Note that for these 60 g/m^2 sheets the press-drying effect was destroyed at high temperature.

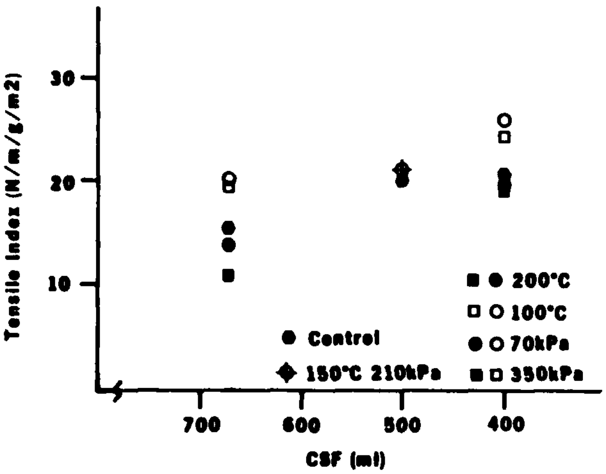

Figure 7 - Tensile Index versus CSF

Figure 8 is similar to Figure 7, but at 64% yield. The press-drying effect is maintained at 400 CSF, yet confusion reigns at 200 CSF.

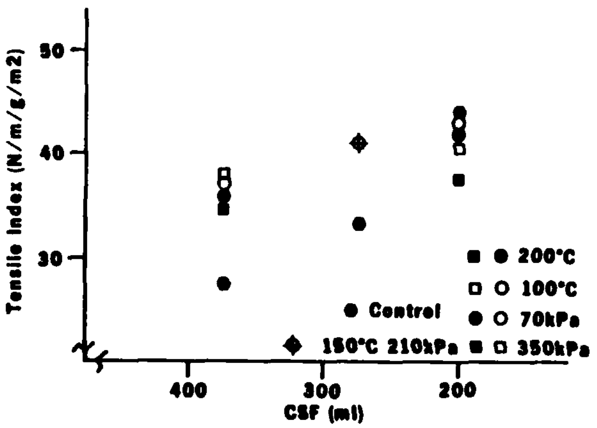

Figure 8 - Tensile Index versus CSF

Figure 9 is a plot of TAPPI opacity versus CSF at 81% yield. Note the direct effect of temperature on opacity, which supports the strength results if one equates lower opacity with fiber bonding.

CONCLUSIONS

The analysis of the drying data strongly suggests that the press drying process is behaving a bit differently than lower-rate, conventional processes. The phenomena of very high drying rates and consequent need for rapid vapor removal, coupled with thermoplastic flow of certain polymers has created an unique drying sit-

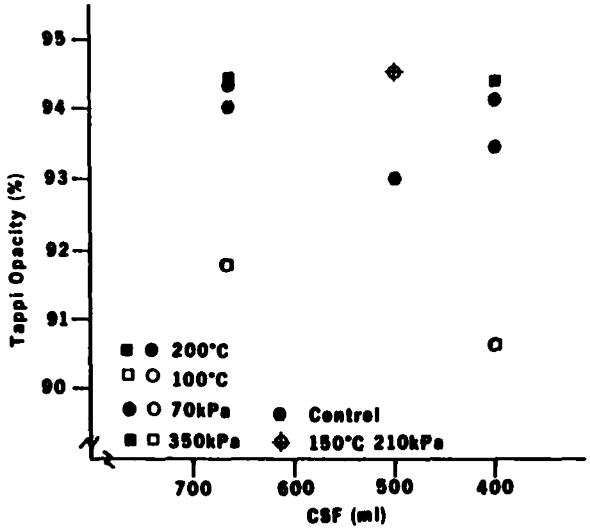

Figure 9 - TAPPI Opacity versus CSF

uation. More detailed and fundamental drying studies will need to be done in order to understand and properly model the mechanisms important in press drying.

Press-drying will show improvements in physical property development over conventional drying methods for high freeness pulps at basis weights as low as 60 g/m^2. To obtain maximum benefit, temperatures as low as possible should be used. Fine mesh screens will improve results, as will higher press pressures, with both of these variables affecting results in an asymptotic fashion. Press-drying does not yield benefits at low freenesses where fiber conformability is adequate for good bonding.

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PRESS DRYING OR DRY PRESSING[1]

Gregory L. Wedel[2]

INTRODUCTION

Substantial improvements in both wet and dry paper strength properties have been achieved by statically pressing a sheet of paper between two heated platens while simultaneously drying -- a process that has come to be called press drying. These improvements in strength properties have generated considerable interest in the paper industry, and have been shown to have a very significant economic impact on the overall cost of paper manufacture -- <u>if</u> the improvements can be achieved on a commercial scale.

There were two fundamental areas of research which needed attention when press drying was first introduced: determining the fiber bonding mechanisms that produce these effects, and determining the process parameters which would cause these bonding mechanisms to occur. Despite the considerable efforts which have been directed toward understanding the press-drying process, these two areas of research still need attention today.

The work reported here was directed toward the second of the above two areas -- identifying the necessary process parameters. Accurate definition of the process requirements is needed in order to evaluate the technical feasibility of the process and to direct the development of the associated machinery, should the process prove to be viable.

The press drying process parameters which require evaluation include the temperature, pressure, restraint, and time. Each of these parameters can be combined with any of the others, in varying degrees, in processing the wet web. Two of these parameters -- pressure and time -- have already been evaluated separately from the other two. Extensive research in the area of wet pressing has shown that significant gains in sheet densification, and the associated gains in dry strength, can be achieved by pressing alone. The present study can therefore be viewed as one which is directed at determining how much of the press-dried paper strength can be achieved by pressing, and how much additional strength can be developed by subsequent drying restraint. Specifically, data is taken which will allow direct comparison of the press dried sheet strength to the strength of sheets which are pressed according to current commercial standards.

TEST ASSEMBLIES

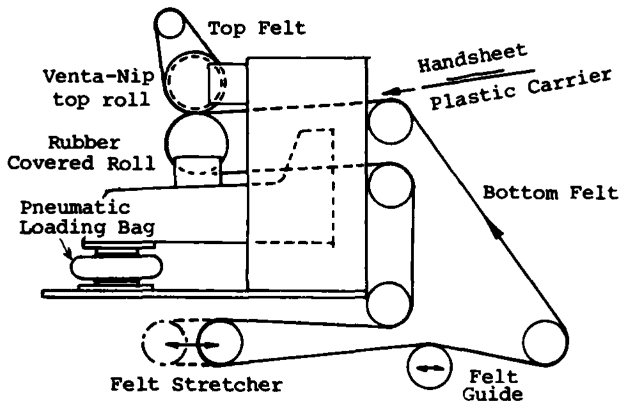

Figure 1.--Wet pressing apparatus.

In order to evaluate the separate potentials of wet pressing and drying restraint, two test assemblies were developed. The first assembly, shown in Figure 1, is a double-felted, two-roll, laboratory press. This press was used to simulate the commercial wet pressing. The speed, loading, and number of passes could be independently adjusted to achieve the required outgoing press dryness.

The second assembly, shown in Figure 2, consists of two temperature-controlled copper platens, capable of applying restraint pressures up to 345 kPa (50 psi) while the sheet is drying.

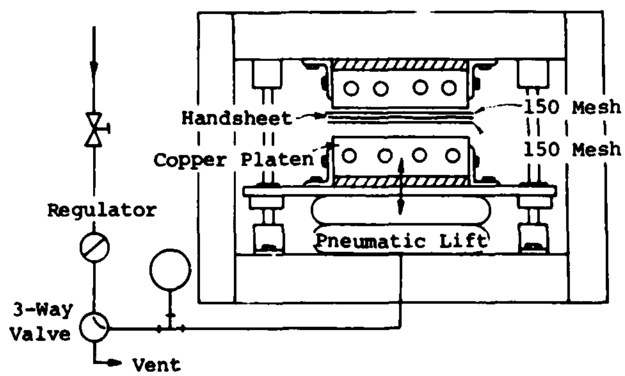

Figure 2.--Restraint drying apparatus.

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[1] Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2] Gregory L. Wedel is Manager of Drying Research, Beloit Corporation, Beloit, Wisc.

Table 1.--Press drying test data. Mixed southern hardwood species, 61% yield, 650 CSF, 2.48 WRV. Press conditions: 46 mpm (150 fpm) at room temperature. Drying conditions: 121°C (250°F) platens with web sandwiched between 150 mesh screens.

Run No.	Pressing Parameters Pass	*	Press Moisture g/g	% dry	Drying Restraint kPa	psi	SHEET PROPERTIES Basis Weight g/m^2	Density g/cm^3	Tensile Index Nm/g	Burst Index $kPam^2/g$
5.01	2	1	1.58	38.8	2.28	0.33	209	0.483	38.3	2.23
5.02	2	1	1.57	38.9	2.28	0.33	206	0.512	40.2	2.28
5.03	2	1	1.57	38.9	13.8	2.00	209	0.544	44.6	2.41
5.04	2	1	1.58	38.8	13.8	2.00	207	0.542	43.8	2.49
5.05	2	1	1.59	38.6	138	20.0	207	0.677	56.1	3.51
5.06	2	1	1.58	38.8	138	20.0	208	0.715	57.2	3.34
5.07	2	1	1.58	38.8	345	50.0	208	0.754	59.4	3.63
5.08	2	1	1.57	38.9	345	50.0	209	0.760	59.0	3.39
5.09	5	2	.98	50.5	2.28	0.33	208	0.736	53.7	3.61
5.10	5	2	.98	50.5	2.28	0.33	210	0.735	54.2	4.01
5.11	5	2	.95	51.3	13.8	2.00	206	0.750	59.8	4.02
5.12	5	2	.99	50.3	13.8	2.00	206	0.769	60.8	3.41
5.13	5	2	.97	50.8	138	20.0	208	0.817	63.4	4.43
5.14	5	2	.97	50.8	138	20.0	211	0.789	70.9	4.21
5.15	5	2	.98	50.5	345	50.0	211	0.863	69.3	4.21
5.16	5	2	.98	50.5	345	50.0	210	0.840	67.1	4.22
5.17	35	3	.69	59.2	2.28	0.33	218	0.921	62.1	4.94
5.18	35	3	.69	59.2	2.28	0.33	218	0.909	66.3	4.75
5.19	35	3	.69	59.2	13.8	2.00	220	0.969	72.6	5.04
5.20	35	3	.68	59.5	13.8	2.00	215	0.970	75.0	4.68
5.21	35	3	.69	59.2	138	20.0	217	0.947	64.1	4.90
5.22	35	3	.69	59.2	138	20.0	220	0.991	69.0	4.89
5.23	35	3	.70	58.8	345	50.0	220	0.969	70.9	4.94
5.24	35	3	.69	59.2	345	50.0	216	0.963	69.7	4.64

* 1 20.7, 38.5 kN/m
2 20.7, 38.5, 75.3, 2 x 231 kN/m
3 20.7, 38.5, 75.3, 32 x 231 kN/m

5.71 pli = kN/m

TEST PROCEDURES

Handsheets of 200 g/m^2 weight were prepared from a high yield (61%) mixture of southern hardwood species, lightly refined to a freeness of 650 ml CSF and a Water Retention Value of 2.48, as measured by TAPPI UM 256.

The handsheets were then placed on a 0.040" thick flexible plastic carrier and wet-pressed in the Figure 1 apparatus. The impermeable carrier was used to insure that the handsheet immediately separated from the felt as it exited the nip so that any rewetting potential was minimized. The potential for rewet was further reduced by running the press at 46 mpm (150 fpm) which is safely above the speed at which rewet is significant for this pulp.

The press loading was increased after each pass, and the moisture content measured after the final pass. In all of these tests, the handsheets were pressed at room temperature to insure that little thermal dewatering took place.

After wet pressing, the handsheets were dried under Z-direction restraint between the two heated platens of the Figure 2 apparatus. In order to provide adequate ventilation of the evaporated water, the handsheets were sandwiched between (6) 150 mesh wire screens. One of these screens was above the web, in contact with the top platen, and the rest were below the web, in contact with the lower platen. The platen temperatures were maintained at 120°C (250°F).

The platens were held together by a pneumatic bag which applied a pre-determined pressure on the handsheet until it was dry. About 5 minutes were allowed for the drying process.

After drying, the handsheets were conditioned for at least 24 hours at 50% relative humidity and 23°C. The following sheet properties were then determined: basis weight (TAPPI T410), caliper (T411), dry tensile (T494), and burst (T403). The results are given in Table 1.

RESULTS

The three sheet properties -- density, tensile index, and burst index -- are shown in Figures 3 - 5 as functions of the outgoing press moisture content. Each figure has four curves, one for each level of drying restraint pressure which was applied after the sheet had been wet pressed.

The data show that increased wet pressing

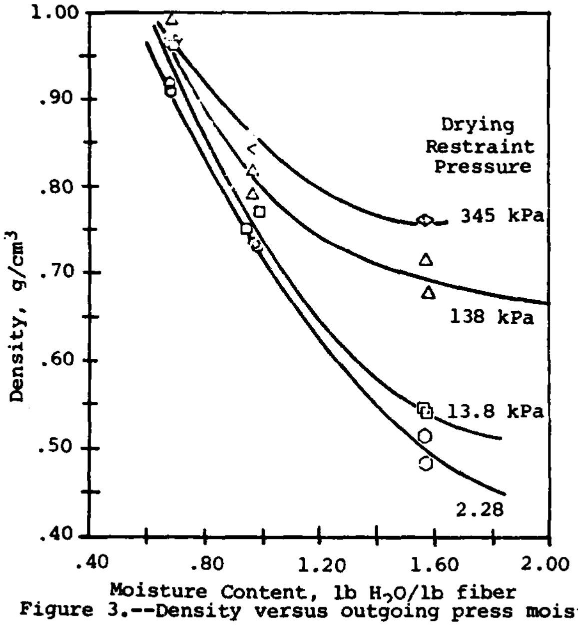

Figure 3.--Density versus outgoing press moisture content.

(decreased moisture content) can have a very significant and positive effect on the sheet strength, even when the web is subsequently dried at conventional low restraint pressures.

On the other hand, the data also show that high levels of drying restraint pressure can also have a very significant and positive effect on the sheet strength, even without pressing to high dryness levels.

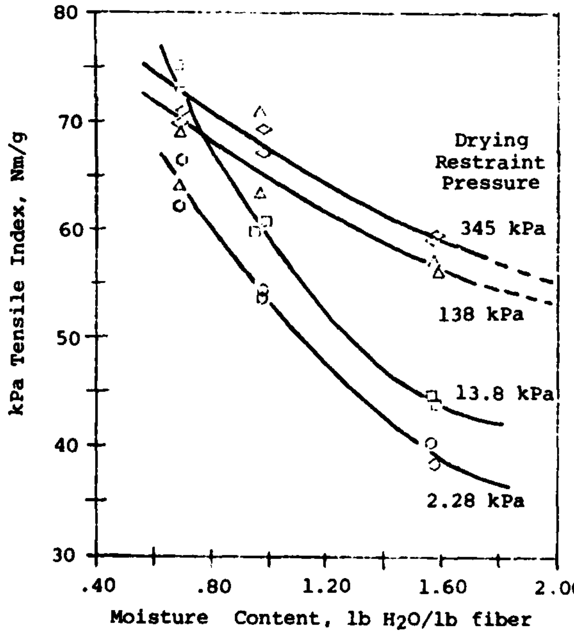

Figure 4.--Tensile index versus outgoing press moisture content.

Both processes represent sheet densification with accompanying increases in strength properties. However, in order to determine if the resultant properties have the <u>same</u> functional relationship to density, the tensile and burst indexes are shown as functions of the equilibrated sheet den-

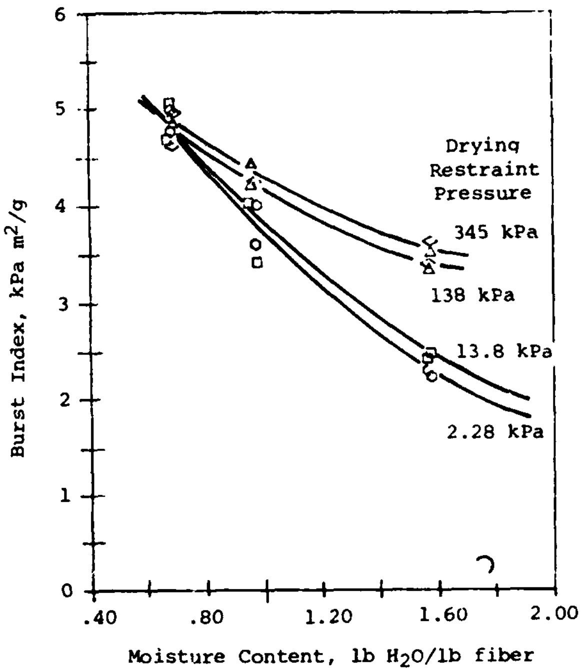

Figure 5.--Burst index versus outgoing press moisture content.

sity in Figures 6 and 7. These curves show that both wet pressing and drying restraint, although distinctively different processes, produce the same dry strength when the same density is achieved.

That is, both processes represent densification of the web and the resultant strength is virtually independent of the path by which the densification was achieved.

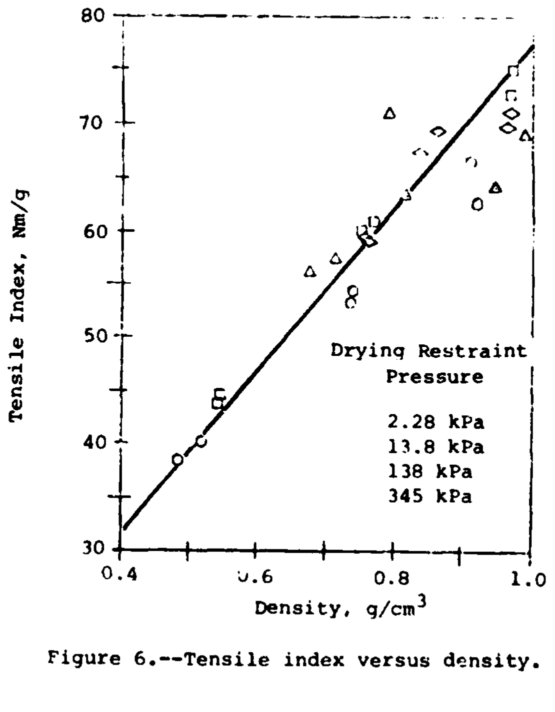

Figure 6.--Tensile index versus density.

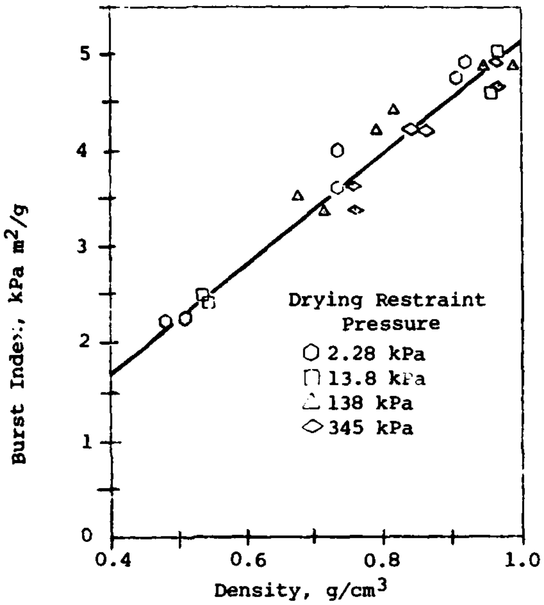

Figure 7.--Burst index versus density.

CONCLUSIONS

In contrast to most other investigations of press drying, this study concentrated on the effect of drying restraint after the pressing part had been completed. This has the significance of allowing evaluation of the separate contributions of pressing and drying in the development of dry web strength. One obvious short-coming of the test assemblies, however, was that the drying restraint was not applied immediately after the pressing. There is ample time for the wet compressed web to spring back after the pressing. It is the author's opinion that this is not significant. A press dryer similar to the FPL pilot unit could be used to investigate this aspect in more detail.

It is possible, with modern wet pressing technology, to achieve high outgoing press dryness. For this particular pulp, drynesses in the range of 50-55% can be achieved. This corresponds to densities in the range of 0.75-0.83 g/cm^3 with the tensile index in the range of 53-58 Nm/g. This tensile strength is 35% higher than the strength which would be achieved by wet pressing to only 40% dry, with both presses being followed by drying under low level restraint.

This study also shows that there is another path by which high densities and high dry strengths can be achieved. This path requires the continuous application of x-y-z-direction restraint to the wet sheet until it is dry. The pressure which must be applied depends on the amount of initial densification which was achieved by wet pressing.

For example, in order to achieve a density of 0.77 g/cm^3 (Figure 3), an outgoing wet press moisture ratio of 1.00 (50% dry) would be required if the sheet will subsequently be dried under low restraint pressures. In order to achieve the same density with a sheet which is wet pressed to a moisture ratio of 1.50 (only 40% dry), the pressure which must be applied during the subsequent restraint drying is 138 kPa (20 psi).

In the above example, the 138 kPa drying restraint pressure could be achieved by wrapping a standard 6-foot diameter dryer with a tensioned wire or fabric or belt. Although 138 kPa (20 psi) may appear to be a small value, it is not. The required wire tension would be 126 kN/m (720 pli), the wire rolls would have to be 1.37 m (4.5 ft) in diameter, and the journals and bearings of the "standard" 6-foot dryer would fail. That is, the mechanical equipment required to apply even a 138 kPa restraint to the sheet would require a major departure from conventional dryer section design.

During the restraint drying process, the web

Table 2.--Comparison of Pressing Force and Time
Linerboard Machine - 7620 mm trim (300")

Description	Pressing kN/m	Pressing PLI	Drying	Total Force 10^6N	Total Force 10^6lb.
Conventional (press to 38% dry)	140 175 210	800 1000 1200	2.38 kPa x 200 m (0.33 psi x 660 ft)	7.49	1.68
ENP (press to 50% dry)	140 175 1050	800 1000 6000	2.38 kPa x 122 m) (0.33 psi x 400 ft)	12.5	2.82
Restraint Drying (press to 38% dry) (double drying rate)	140 175 210	800 1000 1200	138 kPa x 100 m (20 psi x 330 ft)	110.	24.7
High Temp. Drying (press to 38% dry) (web at 140°C, 285°F)	140 175 210	800 1000 1200	276 kPa Sat. Pressure Hood: 6.1 m x 122 m x 7.62 m (40 psi - 20' x 400' x 300")	949.	213.

in these tests was well-ventilated, and the web temperature never exceeded 97°C (210°F) during the drying cycle. Practical means for achieving and maintaining the high vapor pressures which correspond to higher web temperatures have not yet been proposed. Consequently, this study was directed at currently achievable web temperatures.

In order to further illustrate the difficulties associated with achieving high restraint pressures or high web temperatures, a comparison of the forces involved is given in Table 2. The first listing is representative of a commercial 7620 mm (300") wide linerboard machine: 3 presses followed by 200 m (660 ft) of dryer surface covered by dryer felts. The total pressing force for this arrangement is 7.5 million Newtons (1.7 million pounds).

By replacing the third press with a 1050 kN/m (6000 pli) ENP and reducing the dryer length to 122 m (400 ft), the total force increases to over 12.5 million Newtons (2.8 million pounds). This represents a sizeable increase in force, and requires a significant step in technology.

If the standard 3-press arrangement is followed instead by a restraint dryer which applies a 138 kPa (20 psi) pressure to the web, the total force which must be contained increases by more than one order-of-magnitude, even if the drying rate doubles.

If, instead, the web temperature is to be increased to 140°C (285°F) and maintained at that level throughout the drying process, then the applied forces must contain a pressure of 276 kPa or 40 psig (the saturation pressure). This could, in concept, be achieved by drying the web inside a pressurized chamber, perhaps similar to a Minton dryer hood which is under pressure instead of vacuum. The total force which is required for this approach is more than two orders-of-magnitude larger than those of the conventional paper machine.

In a very simple sense, the cost of paper machinery is proportional to the forces involved. Larger forces must be constrained by larger structures, and the cost of machinery is, at least in this simple sense, tied directly to the size.

The above examples illustrate the difficulties associated with bringing the press-drying concept into commercial reality. The cost and complexity of the associated machinery makes other alternatives look much more attractive. Since the dry strength properties appear from this study to be dependent on density alone, the required density will continue to be achieved by wet pressing to higher dryness levels (dry pressing) rather than by press-drying, at least until the process requirements are more clearly understood and a viable arrangement of press-dryer can be proposed and developed.

Processes

CONCEPTUAL DESIGN OF COMMERCIAL SCALE PRESS DRYING SYSTEM[1]

Robert A. Daane[2]

INTRODUCTION

In the development of the press-drying innovation at the Forest Products Laboratory (FPL) from the original handsheet experiments through the low-speed continuous papermaking runs up to the current dynamic simulations, two essential features of the process have been established to be: (1) pressing a wet sheet or web at a temperature near the boiling point of water, and (2) followed by drying under restraints in all three directions. Under these two broad conditions, the linerboard made of a high-yield red oak kraft pulp has attained strength properties superior to the southern pine varieties.

The dynamic simulator was recently built at FPL to test the press drying of individual sheet samples in very short nip residence times of milliseconds as compared with seconds in the original experiments and tenths of seconds in the continuous runs. With this apparatus, a handsheet or sample taken from the Fourdrinier press section is moved through a sequence of heating, pressing, and drying at preset pressures, temperatures, and times. The experimentation with this simulator is continuing and, as of this writing, we do not have a definitive set of necessary and sufficient conditions required for successful press drying.

However, the evidence from all of the various experiments so far suggests the necessity and sufficiency of certain conditions which will be described in the next section. It is the task of this report to describe what is considered to be the most effective and most feasible press-dryer design concept which will meet these conditions.

PROCESS AND GENERAL APPROACH

Hot Pressing

The process calls for pressing the paperboard web with high intensity while it is at as high a temperature as feasible. The moisture in the web as it approaches this high intensity press nip should be just enough so that it will become saturated in the nip. This minimum amount of moisture is needed to contribute to the softening of the fibers and of the hemicellulose. More moisture than this will make it necessary to expel water in the nip, and this will resist the maximum compaction of the paperboard web. The hot press should use a small diameter, highly loaded pressure roll. This may seem to contradict experimental evidence on the FPL pilot machine, since nip dwelltime was very long in that case due to low speed. On the FPL dynamic simulator, with 9-inch-diameter press rolls, long dwelltime (low speed) did improve web properties. But this was only true at very low speeds. Above speeds which would simulate commercial practice, nip dwelltime did not seem to make any difference. Therefore, it appears to be of no benefit to increase the high pressure nip length from a fraction of an inch even to several inches.

It is estimated that the desired moisture content in the web as it enters the high intensity, hot-press nip is about 40%. If possible, this dryness should be obtained by wet pressing rather than predrying by evaporation, so that the moisture distribution through the web thickness is uniform rather than dry on the web surfaces and wet in the interior. Then the softening effects of the moisture are available at the web surfaces as well as in the interior, and waterflow during pressing is minimized.

Drying With Z-Direction Pressure

The second part of the process is to dry the web while it is under restraint in all three directions. Sufficient restraint can be provided by a Z-direction pressure of a few psi. During drying, the web should be at as high a temperature as feasible. The web should be carried from the hot press to the dryer with minimum travel distance and minimum exposure to air in order to minimize relaxation of the compaction and to minimize drying without restraint. Similar unrestrained and exposed web travel distances during the low pressure press-drying period must also be minimized. At the present time, the seriousness of interruption of restraint between the hot pressing and during the press drying is not known.

For this main part of the process, i.e., the drying with Z-direction pressure applied as

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[1]Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2]Robert A. Daane is a Mechanical Engineer and Consultant. The full report was prepared under Research Agreement FP-80-0242 for the Forest Products Laboratory.

continuously as possible, I recommend the use of a version of the CONVAC drying method which was invented by J. A. Lehtinen, a consultant to Tempella Engineering Works (1978, 1980). I was not able to obtain from Mr. Lehtinen any information on how he intends to reduce to actual practice the drying method described in his paper and patent. Therefore, the materials, sizes, arrangements, etc., which are presented in this report, are my own recommendations and are not to be considered recommendations on the part of Mr. Lehtinen or Tampella.

DESCRIPTION OF RECOMMENDED SYSTEM

The recommended press-drying system is illustrated by figures 1 and 2. This system is sized to press dry 42-lb linerboard from 45% moisture to 4% moisture at a speed of 1,200 fpm. Other projected operating quantities of interest are shown in table 1. Since the estimated desired moisture entering the dryer is only 40% or perhaps less, the speed of 1,200 fpm is conservatively stated, and the system will probably be capable of a higher speed, approaching 1,500 fpm.

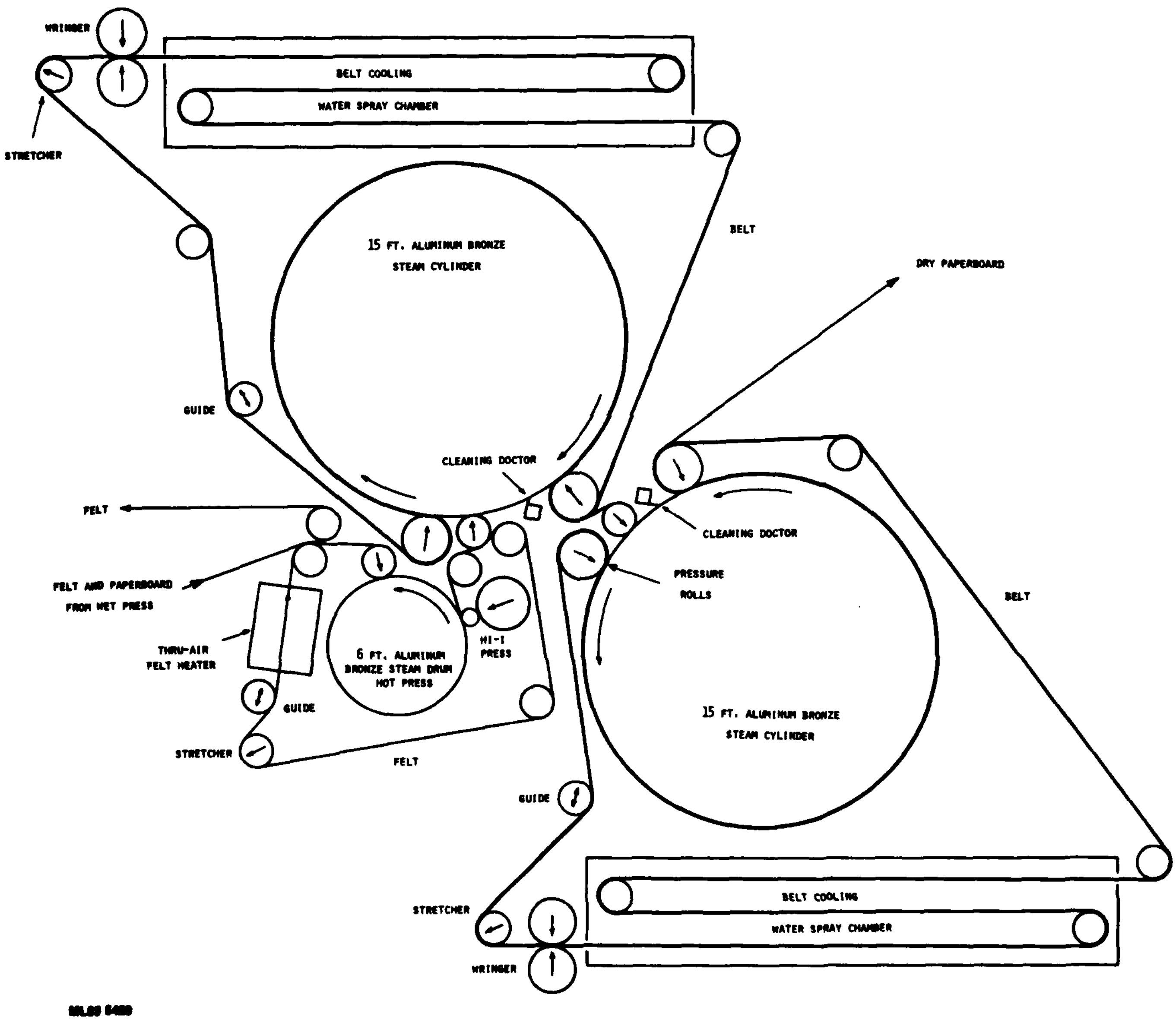

Figure 1.--Two-cylinder press dryer.

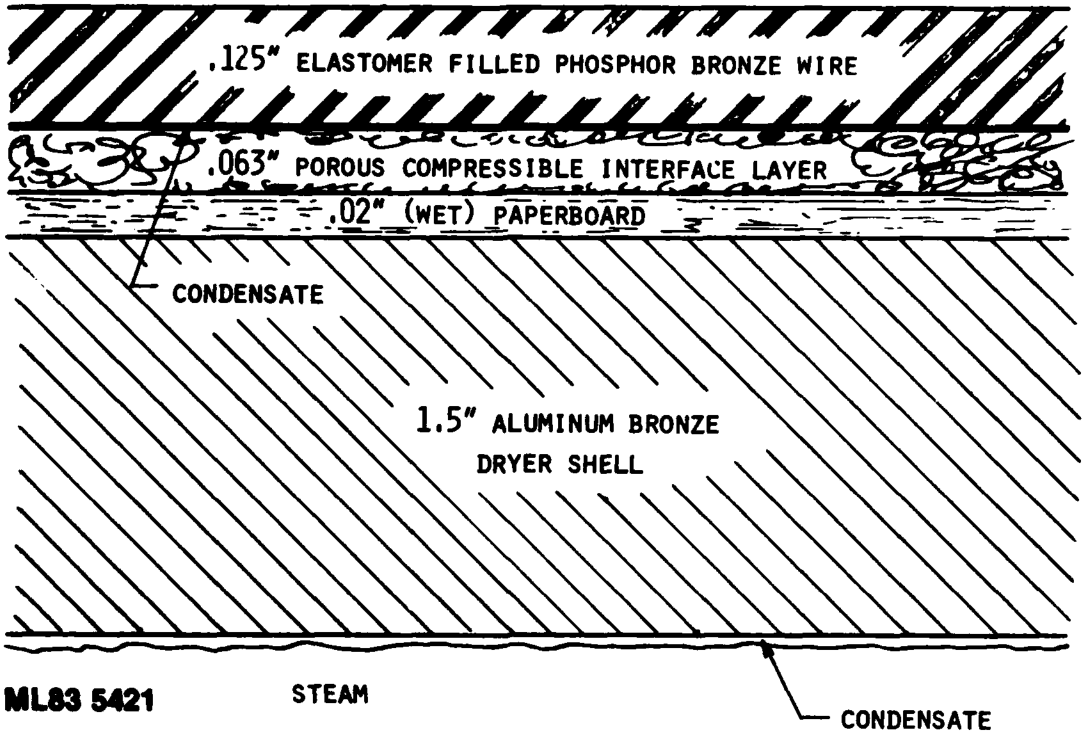

Figure 2.--Cross section of dryer shell, paperboard, and cold belt.

Since we do not need to limit cylinder size with regard to maintaining Z-direction pressure, a very large cylinder diameter of 15 feet is chosen so that we can minimize the number of web transfers and gaps in Z-direction pressure.

Table 1.--Projected overall operation
Web: 42-pound linerboard
Speed: 1,200 fpm
Width: 200 inches

Location	Web moisture (wet basis)	Web temperature
	(%)	(°F)
Entering 6-foot diameter hot-press cylinder	45	120
At high intensity press nip	44.5	203
Entering first 15-foot-diameter steam cylinder	43	190
Entering second 15-foot-diameter steam cylinder	27	203
At end of second 15-foot-diameter steam cylinder	4	219
Overall drying rate on two 15-foot steam cylinders (26.4 lb/hr-ft²)		

My computer program which simulates the drying of webs, was modified so as to handle CONVAC-type drying. The performance predictions, temperatures, moistures, etc., which follow, are based on computer runs using that program.

Referring to figure 1, the paperboard web coming from the wet press first passes around a 6-foot-diameter steam cylinder on which it is to be heated to about 200°F with minimum evaporation. To prevent evaporation, the web is covered by a conventional press felt while it is on the preheating steam cyclinder. At the end of the wrap on the 6-foot-diameter steam cylinder, the web is pressed with high intensity by a press arrangement similar to the HI-I press developed by Black-Clawson several years back. This type of press arrangement is used so that we can get high intensity pressure applied without having a very large line loading in pli imposed upon the steam cylinder. Table 2 shows the various operating parameters for this part of the process.

The paperboard web is then transferred to the first 15-foot-diameter steam dryer cylinder. An impermeable, cold belt, cooled by a water spray chamber, as shown, is then laid on this cylinder so as to cover the paperboard web. Referring to figure 2, the paperboard web is dried by heat from the steam-heated cylinder. The evaporated moisture, driven partly by very small total pressure differences and by diffusion, flows through the porous layer attached to the cold belt and condenses on the inner surface of the cold belt. Most of the condensate accumulates at the inner surface of the nonporous

Table 2.--Hot high-intensity press

Item	Description
Steam cylinder:	
Material:	Aluminum bronze (see table 4)
Diameter:	6 ft
Shell thickness:	2.25 in.
Allowable nip load:	200 pli
Steam pressure:	125 psig (350°F)
Condensate coefficient:	1,000 Btu/hr-ft^2-°F
Felt properties (dry uncompressed, running condition):	
Material:	Needled nylon
Weight:	4.5 oz/ft^2
Porosity:	62%
Caliper:	0.125 in.
Specific heat:	0.35 Btu/lb-°F
Thermal conductivity:	0.04 Btu/hr-ft-°F
High intensity press nip roll:	
Diameter:	9 in.
Nip loading	600 pli
Through-air felt heater:	
Length:	4 ft
Air temperature:	300°F
Felt temperature, in:	195°F
Felt temperature, out:	201°F
Air flow rate:	8,400 cfm (at 300°F)
Pressure drop:	12 in. W.C.
Air horsepower:	16 hp

part of the cold belt, being held there partly by centrifugal force.

A substantial part of the air is driven out of the paperboard web and the porous layer attached to the cold belt by means of the pressure roll which applies the belt to the steam cylinder. The total pressure of the air-vapor mixture in the porous paperboard web and in the porous interface layer of the cold belt is then maintained at a subatmospheric level depending upon the belt and paperboard temperatures.

The paperboard web is then transferred to a second 15-foot-diameter steam cylinder having a similar cold belt wrap configuration as the first cylinder. The web is dried to a final dryness on this second cylinder. Table 3 shows the various specifications and operating parameters for the steam dryer cylinders, the cold belt, the cold belt interface layer, the pressure rolls, the cold belt chiller, and the wringer press to remove water from the porous part of the cold belt.

Except for a length of travel of about 6 feet while the paper web is being transferred from the hot press nip to the first 15-foot steam cylinder and about 5-1/2 feet while it is being transferred from the first 15-foot steam cylinder to the second, a Z-direction pressure is maintained on the paperboard web in the amount equal to the vacuum maintained in the space between the impermeable part of the cold belt and the steam cylinder surface. Thus, except for these unavoidable interruptions during sheet transfer, the desired conditions for press drying are provided. There will be an adjustable trade off between the Z-direction pressure on the web and the web temperature during the drying period. However, it will be possible to maintain both values at levels which appear to be sufficient for successful press drying, based on the results of the FPL pilot machine experiments.

It is recommended that all three of the steam-heated cylinders be made out of aluminum bronze in order to maximize heat transfer and thus minimize the number of cylinders needed, as discussed earlier. The mechanical and thermal properties of the aluminum bronze are shown in table 4.

ENERGY CONSIDERATIONS

As with any drying process, there will, of course, be some energy losses detracting from the efficiency of the process. With the proposed system, these losses are very small. In fact, it is anticipated that the thermal efficiency of the system would be an astonishingly high 94%. This is high compared with conventional drying systems because they almost always involve a rather large heat loss to ventilating air. Such a loss is eliminated almost entirely with the proposed system because there need be almost no ventilation at all. However, we must add the losses associated with the dryer cylinder condensate removal system. With large-diameter steam dryer cylinders, a rather large amount of blow-through steam is needed in order to properly evacuate condensate and to maintain a low amount of condensate within the dryer shell and thus to maintain a high condensate heat transfer coefficient. This problem is to some extent alleviated by the use of the proposed spoiler bars for generating turbulence in the condensate. This, together with the use of efficient thermocompressors can control the blow through heat loss to the extent that it is estimated that the overall thermal efficiency will be a very respectable 85%.

ALTERNATIVES

It is possible that continuing work at FPL will show that the losses in effectiveness of press drying due to interruptions in the Z-direction pressure during transfer of the paperboard web from the hot press to the dryer

Table 3.--The CONVAC type dryers

Item	Description	Item	Description
Steam cylinders:		Cold belt, outer layer:	
Material:	Aluminum bronze (see table 4)	Thickness:	0.125 in.
		Phosphor bronze wire:	33% by volume
Diameter:	15 ft	Polyurethane filler:	67% by volume
Shell thickness:	1.5 in.	Composite weight:	2.36 lb/ft^2
Allowable nip loading:	500 pli	Composite density:	227 lb/ft^3
Steam pressure:	125 psig (350°F)	Composite specific heat:	0.132 Btu/lb-°F
Condensate coefficient:	1,000 $Btu/hr\text{-}ft^2\text{-}°F$	Composite thermal conductivity:	4.97 Btu/hr-ft-°F
Pressure rolls:			
Paper application roll:	17 in. dia., 75 pli	Cold belt, interface layer (with 5 psi compression):	
Cold belt pressure roll, one per cylinder at point where cold belt is applied onto dryer cylinder:	24 in. dia., 180 pli	Thickness:	0.0625 in.
		Weight:	0.069 lb/ft^2
		Density:	13.2 lb/ft^3
		Specific heat:	0.3 Btu/lb-°F
Cold belt take-off roll, one per cylinder at point where cold belt leaves the dryer cylinder:	24 in. dia., 0 pli*	Thermal conductivity:	0.03 Btu/hr-ft-°F
		Porosity:	80%
		Porosity (with 150 psi compression):	20%
Cold Belt Chiller:	Unit 1	Cold Belt Chiller:	Unit 2
Exposed belt length:	60 ft	Exposed belt length:	60 ft
Belt temperature into chiller:	135°F	Belt temperature into chiller	130°F
Belt temperature out of chiller:	85°F	Belt temperature out of chiller:	85°F
Cooling load:	22.2 x 10^6Btu/hr	Cooling load:	20.0 x 10^6Btu/hr
Water temperature into chiller:	77°F (max)	Water temperature into chiller:	77°F
Water temperature out of chiller:	109°F	Water temperature out of chiller:	109°F
Water flow rate:	1,390 gpm	Water flow rate:	1,360 gpm
Wringer Press (each unit):	24 in. dia., 200 pli	Wringer Press (each unit):	24 in. dia., 200 pli

*Controlled clearance so that the cold belt just makes definite contact with the paperboard with essentially no compression of the belt.

Table 4.--Aluminum bronze properties (at 300°)

Property	Value
Density:	496 lb/ft^3
Thermal conductivity:	48.9 Btu/hr-ft-°F
Specific heat:	0.09 Btu/lb-°F
Modulus of elasticity:	16,000,000 psi
Ultimate strength:	79,000 psi
Yield strength:	39,000 psi

cylinders and between dryer cylinders are very serious. In that event a modification of the proposed press-drying system may still be viable, and perhaps the only viable method of carrying out successful press drying. The modification would be to carry out the entire process on one large steam-heated cylinder. This would limit the speed to about 400 fpm. This might eliminate the process from consideration for many applications, but would perhaps leave it of interest for use in geographic areas where conventional pulp is very scarce.

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HIGH-SPEED SIMULATION OF PRESS DRYING[1]

Dennis E. Gunderson, John F. Hunt, and Vance C. Setterholm[2]

INTRODUCTION

Almost all of the press-drying research reported to date has focused on static (continuous-pressing) processes and pilot-machine processes conducted at speeds less than 15 m/min. Researchers have shown the roles of web densification, of restraint of the web while it is drying, and of the temperature of the web while it is drying, and have proposed a variety of concepts for press drying at production speeds. The results of the static and slow-speed dynamic research suggest that direct scale-up of the static process to production speeds of 700+ m/min presents a significant engineering challenge.

The objectives of this study are to (1) examine some of the significant process variables involved in scale-up of press drying to high speeds, (2) simulate variations of one potentially viable press-dry process, (3) compare the results of the high-speed simulation process with those obtained in a static process, and (4) compare the performance of paperboard produced through high-speed press drying with the performance of a "conventionally dried softwood" paperboard.

BACKGROUND

Press drying has been described as a process in which the wet web is dried under heat and pressure to increase the conformability of fibers, improve interfiber bonding, inhibit "springback" in the Z-direction and prevent shrinkage in the length and width (X and Y) directions. The effectiveness of the static press-drying process is well documented.

Although incorporation of the continuous pressure feature of static press drying in a commercial dryer running at 700+ m/min appears to involve a revolutionary departure from current practice, a concept in which the web is first densified and then dried under modest Z-pressure and X-Y restraint may be achievable in the near-term, based on existing technology. Such a densify-restrain concept will not create the wet-strength enhancement linked to elevated drying temperature as in the static process, but it could conceivably retain other features of the continuous-pressure static process.

We have constructed a special pressing and drying apparatus at the Forest Products Laboratory with which to simulate densify-restrain processes under conditions representative of production speeds of 700 m/min. This apparatus is conceptually illustrated in figure 1. It allows the web to be warmed before pressing, pressed at nip residence times from 2 to 200 msec, and subsequently dried under either continuous or intermittent Z-pressure of 35-70 kPa and X-Y restraint.

EXPERIMENTAL

Scope and Furnishes

An oak furnish was used to evaluate three processes which were variations of the basic densify-restrain concept and a continuous-pressure-and-restraint process. In the continuous-pressure-and-restraint process specimens were statically press dried in a special apparatus which provided full, continuous X-Y restraint and allowed application of a wide range of Z-direction pressures. As a point of reference with commercial materials, the data from these four processes are compared in the results section with performance data for a softwood furnish dried using a conventional process.

Webs for the three densify-restrain processes and the continuous-pressure-and-restraint process were handsheets made from 60% yield, northern red oak, unbleached kraft, refined to 600 ml Canadian Standard Freeness (CSF). Webs for the conventional drying process were machine-run from 53% yield southern pine, unbleached kraft, refined to 535 ml CSF. Rosin size (0.2%) was added.

Densify-Restrain Processes

In the three densify-restrain processes, specimens were first subjected to a high-speed densification routine. Prior to densification, webs were pressed between blotters to produce

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[1]Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2]Dennis E. Gunderson and John F. Hunt are General Engineers and Vance C. Setterholm is Project leader, all in the Criteria for Fiber Product Design project, Forest Products Laboratory, Madison, Wis.

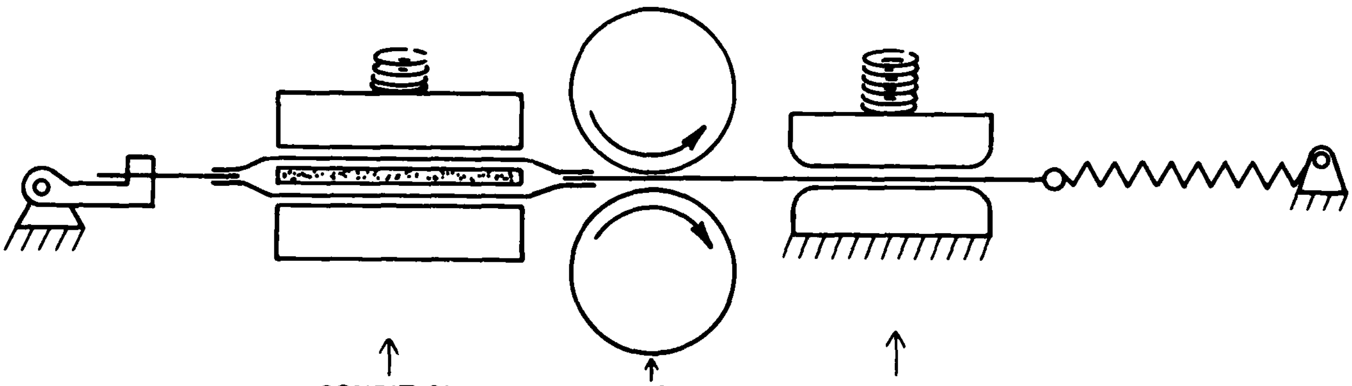

Figure 1.--Three-phase concept of press-dry simulator: Temperature conditioning of the wet web, densification at production equivalent speeds, drying under pressure and restraint. (ML83 5427)

specimens spanning the range from 32% to 71% moisture content.[3] The webs were then warmed to 85° C ± 5° and pressed in a "hard" nip at pressures ranging from 5 to 8 MPa.[4] Nip residence time was 3 msec. The three densify-restrain processes differ in the restraint applied after densification.

PR Process.--Specimens designated PR (pressed and restrained) passed directly from the press nip to a curved drying platen where they were restrained under a wire screen pulled taut over the curved surface of the platen. Z-pressure of 35 kPa was applied by the taut screen until the web was dry.

XY Process.--XY specimens were transferred after pressing to a flat platen press where they were dried under full X-Y restraint but without the application of Z-pressure.

U Process.--U (unrestrained) specimens were dried on the same flat platen as XY specimens but without restraint. U specimens rested on the heated platen and were covered by a dry felt and a heated aluminum block. The block provided a Z-pressure of 1.1 kPa--sufficient to prevent cockling, but not sufficient to inhibit shrinkage of the web as it dried. In all cases, the temperature of the wet web while drying was limited to 100° C.

Continuous-Pressure-and-Restraint Process

The fully restrained specimens are designated FR. This process is similar to normal, static, press drying except that temperature of the wet web is intentionally limited to 100° C. Continuous pressing, at pressures ranging from 35-1,790 kPa, started at web moisture contents of 65%. The apparatus used is schematically portrayed in figure 2.

Conventional Process

The conventionally dried softwood web was formed on a Fourdrinier pilot machine at 10 m/min from stock at 0.69% consistency. It was wet pressed in 3 stages, dried over 17 drums at 130° C and calendered through 1 nip.

RESULTS

Density

The density developed in the roll-pressed specimens is shown in figure 3 as a function of web moisture content at the press. For these single-nipped specimens, density increased as moisture content was reduced. It is also apparent that the modest 35 kPa Z-pressure applied during drying of the PR process contributed significantly to density--particularly at higher moisture levels. Previous results have shown that in this pressing mode density cannot be significantly increased by increasing nip pressure. For the FR specimens, densities from 650 to 950 kg/m^3 were obtained by application of pressing pressures from 35 to 1,800 kPa.[5]

Strength

Tensile index for the FR, PR, U, and XY specimens is plotted as a function of density in figure 4. Performance of FR sheets increased with density and exceeded that of PR and U

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[3]Wet basis. Preliminary investigation showed that the sheet density which could be achieved in a single nip was more dependent on the moisture content of the web than on pressing pressure or residence time.

[4]Average over nip width of 9.5 mm.

[5]FR data would appear in figure 3 as a vertical line at 65% moisture content.

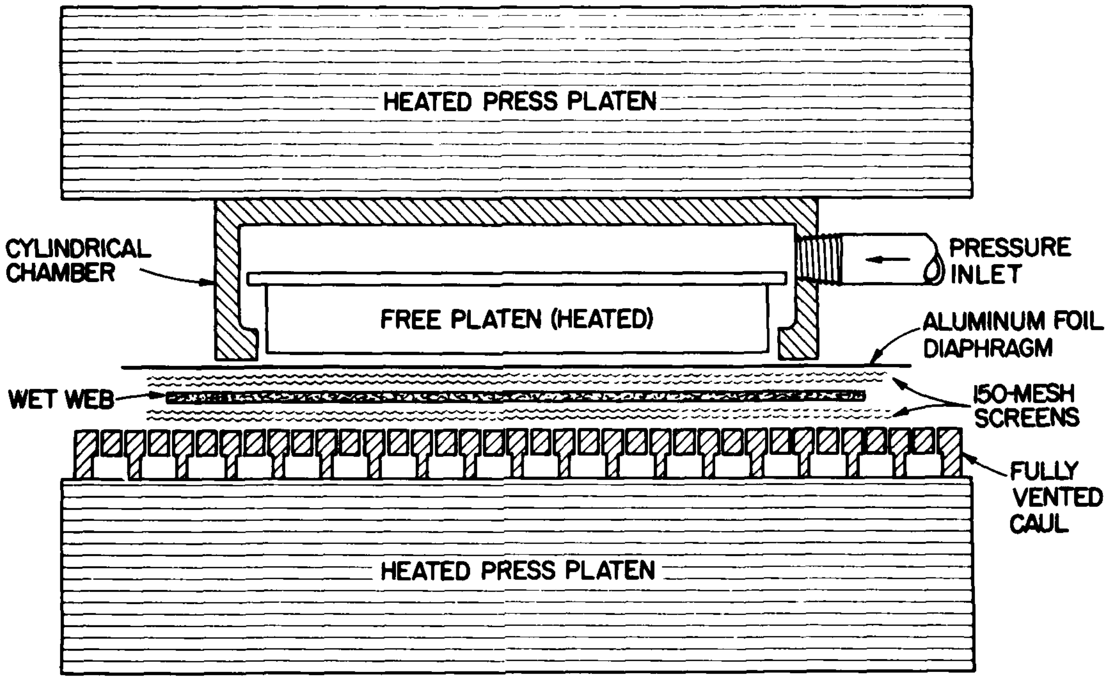

Figure 2.--Apparatus for drying FR (fully restrained) specimens. (ML83 5426)

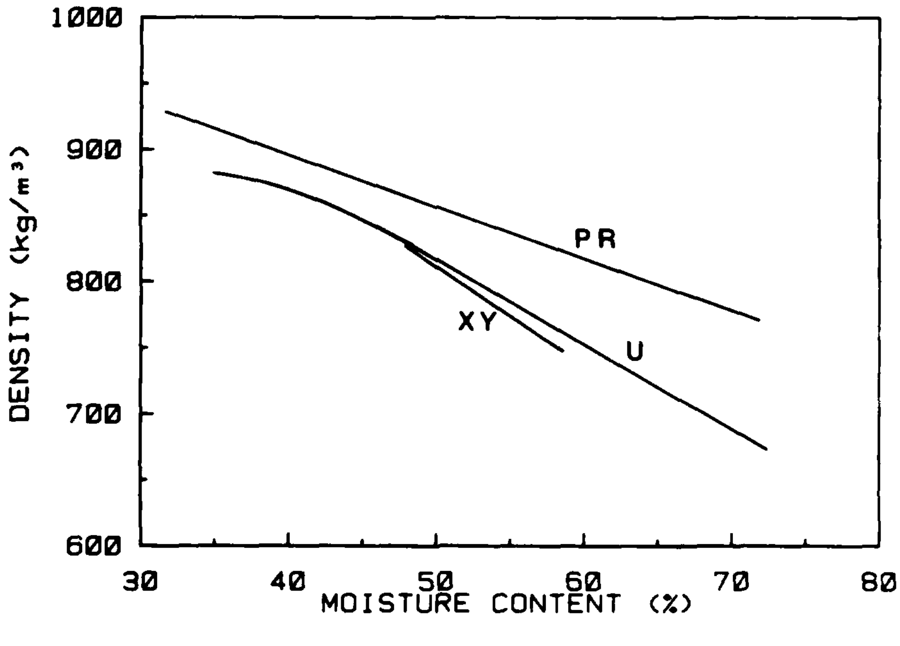

Figure 3.--Density of dried sheets as a function of web moisture content when pressed. PR = pressed and restrained, U = unrestrained after pressing, XY = X-Y restraint only. Pressing pressure, 5-8 MPa. Nip residence time, 3 msec. (ML83 5428)

specimens. PR sheets achieved greater density and generally higher performance than U sheets--but performance declined with increasing density over the range from 775 to 925 kg/m^3. Performance of the XY sheets was lower than the performance of the other three.

Compression index for the FR, PR, U, and XY specimens is plotted as a function of density in figure 5. Performance of FR sheets increased with density up to approximately 850 kg/m^3 density and then began to decline. PR specimens declined in strength over the range from 775 to 925 kg/m^3 whereas the strength of U specimens increased slightly from 675 to 875 kg/m^3. The relative ranking of compressive strength for FR, PR, U, and XY specimens is the same as for tensile strength. This pattern of ranking is consistent for extensional stiffness, ring crush, and burst with the exception that U sheets achieve burst levels equal to PR sheets at comparable densities.

Bending Stiffness

For all processes, stiffness declined with density (fig. 6). FR specimens were from 20% to 55% stiffer than U and PR specimens at equal density.

Folds

MIT fold endurance increased with density for the FR and U processes. Folds for PR declined slightly over the range from 775 to 925 kg/m^3. Only the FR specimens significantly exceeded 200 folds. For the FR process, fold numbers of 500-600 were recorded at densities of 930-940 kg/m^3.

Tensile Strain at Failure

Results for FR, PR, and XY processes were similar, increasing slightly as a function of density. U results increased dramatically with density and exceeded PR results by 40% at a density of 800 kg/m^3.

General

A comparison of physical properties obtained by the various methods is provided in table 1. Density levels were selected to reflect the best overall properties for each process in this experiment. Performance data for a conventionally dried machine-run southern pine kraft are provided for reference. With the exception of bending stiffness, wet strength, and fold endurance, the 60% yield oak handsheets prepared by the PR process performed at a level nearly comparable to the machine-run pine. The U sheets had a greater strain-at-failure than the PR sheets and strengths ranging from 80% to 97% of the strength of the PR sheets. FR sheets, at a density of 925 kg/m^3, were superior to both the pine and other oak sheets. XY-processed sheets were clearly the poorest of the four oak trials.

A somewhat unexpected and disappointing result of this experiment was the tendency of the PR-processed specimens to lose strength and extensional stiffness as density increased--in sharp contrast to the behavior of the FR specimens. We believe two factors are involved, both related to the moisture content of the web prior to pressing. First, it would appear that when moisture is blotted from the web at low temperature and pressure some interfiber water dries up without sufficient Z-pressure to create interfiber bonds. Second, because shrinkage of the unrestrained wet web begins when the moisture content falls below 65%, webs reduced to 40% moisture content can easily have shrunk 1% before densification and restraint begin. We think it possible that the PR process can be improved by multistage densification with continuous control of web shrinkage.

CONCLUSIONS AND RECOMMENDATIONS

A press-drying concept in which the wet web is first densified and then restrained and dried under relatively light Z-pressure is potentially capable of making a competitive paperboard from high-yield, high-freeness oak furnish provided fold endurance, bending stiffness, and wet strength are not limiting factors. Pressing, followed by unrestrained drying, may also be an effective approach for more easily bonded furnishes--subject to the same reservations. Multiple pressing should be explored as a means of densification preferable to the moisture-content-reduction and single-nipping approach studied here.

Continuous application of pressing pressure and restraint (the FR process) is clearly more effective in developing sheet strength and stiffness than the "press-restrain" concepts investigated in this study. In view of the advantages demonstrated in previous research for increasing the temperature of the web during drying and in view of the superiority of continuous pressing and restraint as demonstrated here, we think "elevated-temperature, continuous-press" concepts offer a challenge and an opportunity worthy of considerable investment.

ACKNOWLEDGMENT

The pressing and restraint apparatus shown in figure 2 is an adaptation of an original design by Roy Benson, formerly a Physical Science Technician, Forest Products Laboratory, and now retired.

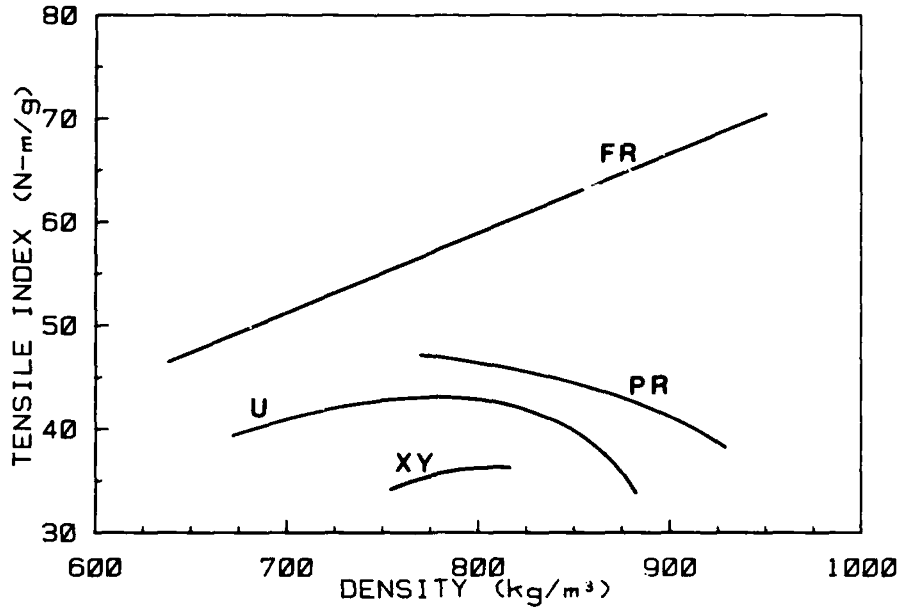

Figure 4.--Tensile index as a function of sheet density. FR = fully restrained, PR = pressed and restrained, U = unrestrained after pressing, XY= X-Y restraint only. (ML83 5429)

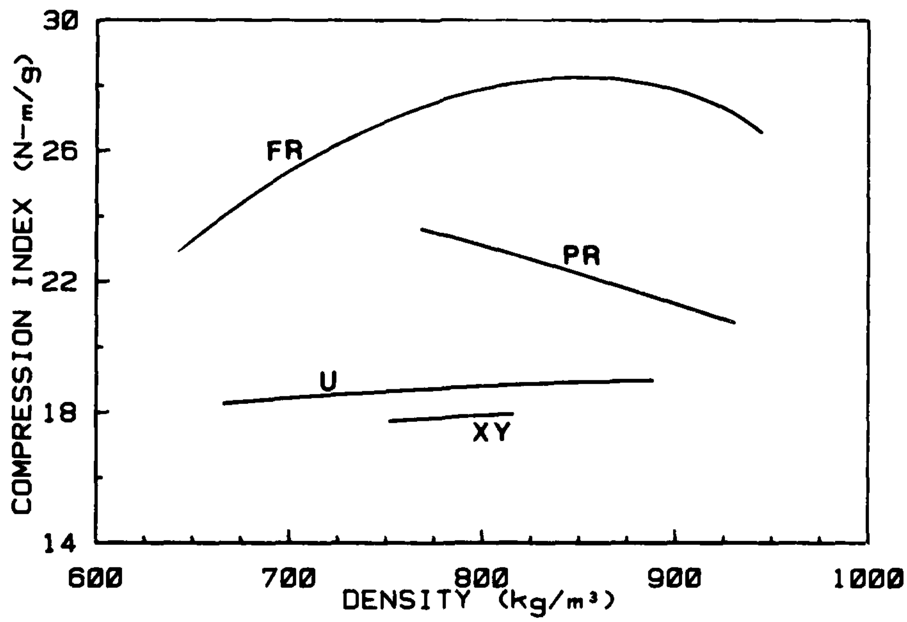

Figure 5.--Compression index as a function of sheet density. FR = fully restrained, PR = pressed and restrained, U = unrestrained after pressing, XY = X-Y restraint only. (ML83 5431)

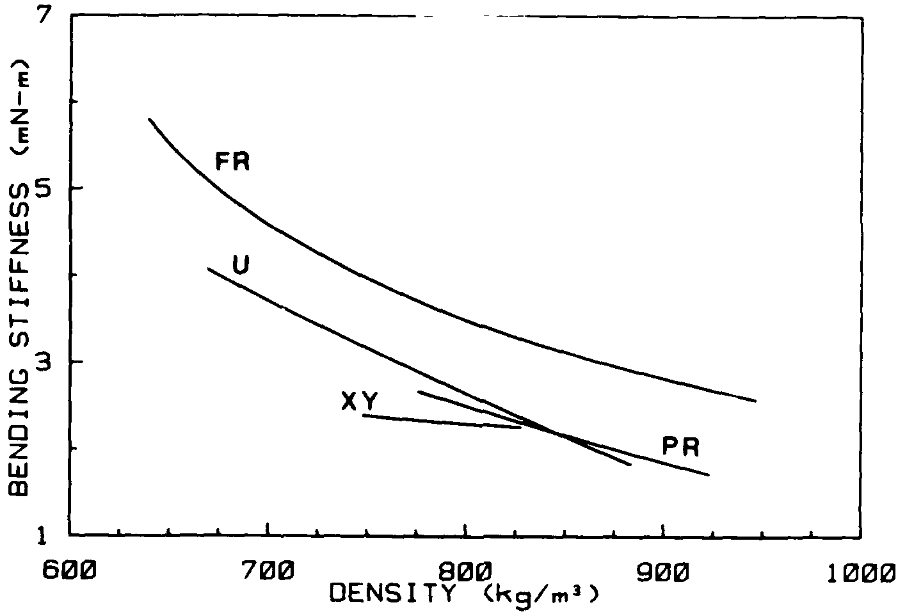

Figure 6.--Bending stiffness (Taber) as a function of sheet density. FR = fully restrained, PR = pressed and restrained, U = unrestrained after pressing, XY = X-Y restraint only. (ML83 5430)

Table 1.--Physical properties at optimum density for four experimental processes[1] applied to oak hand sheets, compared with performance of conventionally dried, machine-run southern pine[2]

Property	Experimental process[3]				Conventional process
	PR	XY	U	FR	
Density (kg/m³)	800	800	800	925	714
Burst index (kPa-m²/g)	3.30	2.27	3.28	4.95	3.38
Tensile index (N-m/g)	46.4	36.2	42.8	68.4	[4]49.7
Extensional stiffness (kN/m)	972	771	811	1,164	[4]963
Tensile strain at failure (%)	3.19	3.38	4.94	3.83	[4]3.24
Compression index (N-m/g)	23.1	17.9	18.8	27.3	[4]20.7
Ring crush strength (kN/m)	3.37	2.34	3.09	4.10	[4]3.28
Bending stiffness (mN-m)	2.50	2.30	2.65	2.69	[4]4.67
Double folds--MIT	166	70	149	360	[4]1,250
Wet tensile strength[5] (kN/m)	0.38	--	--	--	[4]1.18

[1]PR = pressed and restrained, XY = X-Y restraint only, U = unrestrained after pressing, FR = fully restrained.

[2]FPL MR 7210. 100% southern pine, 53% yield, 535 ml CSF freeness. Machine formed @ 0.69% consistency. 0.2% rosin size added.

[3]Temperature of wet web limited to 100°C in all processes.

[4]Geometric mean of machine-direction and cross-machine-direction values.

[5]After 72-hour soak in water at 23° C.

HERTY FOUNDATION PROGRAM PRESS DRYING FACILITIES[1]

J. Robert Hart[2]

INTRODUCTION

The program of press drying at Herty has followed the philosophy of its namesake and founder. Dr. Herty believed that the demonstration of a concept is essential to convince the proper authorities to pursue that concept through to commercialization. Today, it is Herty's endeavor to provide the paper industry with prototype facilities wherein one can witness the pros and cons associated with emerging technology. Although fundamental research is not our purpose, Herty does provide professional assistance and guidance resulting from our experience of working with a wide variety of fibers and end products. The concept of press drying and a related program of developmental work is a typical venture for Herty.

PRESENT STATUS

The present knowledge of press drying that resides at Herty is still infantile. This is evident when every experimental phase or program will create more questions than it will supply answers. The concept is remarkably simple; but the mechanical design and process parameters are very critical. Perhaps the most discouraging aspect (for equipment suppliers) may be the difficulty in protecting their developmental dollars.

A dynamic press dryer model was fabricated at Herty, influenced in design by work previously performed by Brian Attwood. It consists of a 21-inch diameter chrome-plated cylinder with two opposing press rolls. One can apply 140 pli at each nip and operate at speeds of 100 fpm. A continuous fabric maintains web restraint against the cylinder, which can be heated with 120 psi steam. This model has served as a useful tool to verify reported results of other investigators.

Our work has demonstrated both reported advantages of press drying: alteration in the physical properties of the paper and increased rates of water removal. Most of the previous investigations have been directed toward the use of high yield or unbleached pulps. We have applied the press drying technique to a wide variety of pulps, even some synthetic fiber handsheets. Less dramatic strength increases occur whenever one uses "purer" cellulose and non-bonding fibers although spurious results often occur that are difficult to explain.

Regardless of the fiber material in the sheet, we have always observed an increased rate of water removal when the sheet is pressed against the heated surface.

Most all experiments to date have been made with handsheets of varying fiber combinations but without soluble binders or complete fiber furnishes similar to commercial fine-grade papers. It might be expected that wet-end soluble binders may cause the dramatic physical property increases observed with high-yield pulps.

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[1] Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2] J. Robert Hart is Director, Herty Foundation, Savannah, Ga.

FUTURE PLANS

The immediate plans at Herty are to demonstrate press drying on a continuous or steady-state basis. A variety of options are open to us with existing equipment. Of critical importance is the correlation of on-machine data with a laboratory model using handsheets. Without such information, much time would be lost with handsheet evaluation; and the expense of running multiple paper grades of different compositions on a pilot paper machine would be prohibited.

On Herty's existing 36-inch Fourdrinier, we may place nip rolls at various locations in the dryer section. We will avoid excessive loading pressures, perhaps by limiting the width of the nip roll relative to the paper-web width. This also will give us a control sample under identical conditions. An 8-foot diameter Yankee will be available for more elaborate trials with restraining fabrics and multiple press rolls. A modular laboratory press dryer unit is also being considered that can be temporarily put on-machine to assist in obtaining correlation data between steady-state and handsheet operation.

Furthermore, it is Herty's intent to be able to demonstrate as many concepts and conditions as possible. We believe that it is too premature to focus on one mode of operation. We particularly encourage everyone's thoughts and concepts as we plan our prototype facilities.

PRESS DRYING: ITS APPLICATION IN RECYCLED FIBER FOR LINERBOARD[1]

Richard A. Horn[2]

INTRODUCTION

The United States recycles only 22% of its wastepaper, whereas Europe recycles 40% and Japan 50%. American recycling of higher grade products, in particular, suffers because of the availability of low-cost virgin timber. This availability precludes the use of the expensive cleaning practices needed to produce high-grade products from recycled material.

Because of lower cleaning requirements, producing linerboard from recycled materials would be one way to increase the amount of wastepaper recycled in the United States. Unfortunately, conventional processes for making linerboard do not produce a recycled linerboard with sufficient strength. Factors contributing to the loss of strength include the following:

(1) Hornification causes loss of interfiber bonding.
(2) Fines and shorter fibers accumulate in the fiber mass as a result of the succession of repulpings and refinings.
(3) Pulps are often refined to a less than optimal level in order to maintain a reasonable drainage rate on the machine.
(4) Foreign particles, such as clay and pigments, accumulate and increase basis weight without developing a compensating bond strength.
(5) Foreign matter, such as oils, dried starch, and rosin/alum, accumulates and is coated or absorbed on the fibers, interfering with interfiber bonding.
(6) Physical processes, such as calendering and scoring, cut or weaken the fibers which are later to be repulped.

All of the above problems mitigate against increased use of secondary fiber in linerboard manufacture by conventional means of drying. At present, the best commercial practices utilize only about 30% of secondary fiber in a commercial linerboard furnish on Fourdrinier paper machines. The prospects of increasing the use of secondary fiber in linerboard are dim because of strength standards, i.e. Rule 41 of the Uniform Freight Classification (698 kPa for 205 g/m^2 linerboard).

A possible solution to overcome many of the previously mentioned problems, and to increase the use of secondary fiber, may lie in the development of the press-drying process. The concept of press drying has been demonstrated in continuous online drying using a high-yield, unrefined red oak furnish (Horn and Setterholm 1983).

No previous research has been published on the effects of press drying on recycled fiber for linerboard. The objectives of the research reported here were to determine: (1) The effect of press drying on the properties of softwood and hardwood recycled fiber, (2) the feasibility of making acceptable linerboard from 100% secondary fiber using the FPL press dryer pilot machine, and (3) the properties of combined board and corrugated boxes made from press-dried recycled fiber.

RESULTS AND DISCUSSION

Effects on Press-Dried Softwood and Hardwood Recycled Fiber

Differences between softwood and hardwood responses to press drying were observed by testing static press-dried handsheets[3] made from softwood and hardwood recycled fiber. Examples of the effects of conventional and press drying[4] of refined[5] and unrefined recycled southern pine pulp fiber are shown in figures 1 and 2.

Figures 1A and 1B compare the effects of drying a 63% yield southern pine kraft pulp by press drying and conventional drying (Tappi). In each recycle, the furnish was refined to 550 ml Canadian standard freeness.

Probably the most significant effect of press drying is the resultant increase in those sheet properties dependent upon fiber bonding. That press drying does affect fiber bonding is graphically illustrated by the high level of internal bond strength shown by press drying in figure 1C.

The effect of refining is clearly illustrated in figure 1D. If press drying is not

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[1]Paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].
[2]Richard A. Horn is a Research Forest Products Technologist at the Forest Products Laboratory, Madison, Wis.

[3]Basis weight of 205 g/m^2.
[4]Static hot pressing was done at 5.5 MPa, 204°C, for 30 seconds.
[5]Refined in PFI mill at 10% consistency.

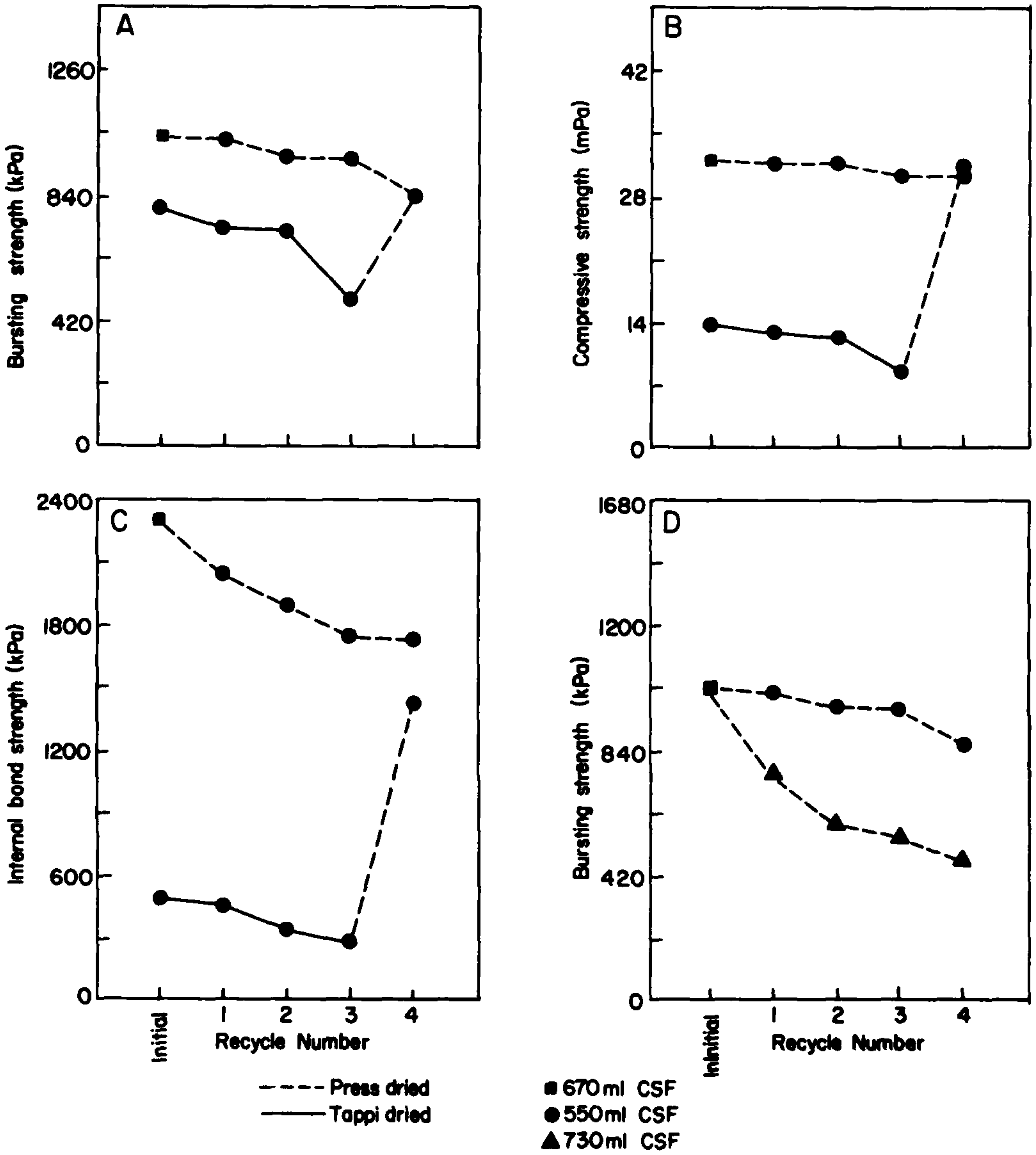

Figure 1.--Physical properties of handsheets made from virgin and recycled 63%-yield southern pine kraft pulp fiber. Basis weight of 205 g/m². (A) Bursting strength, (B) Compressive strength, (C) Internal bond strength, and (D) Bursting strength. In A, B, and C, Tappi-dried sheets were press dried after the third recycle. (ML83 5437)

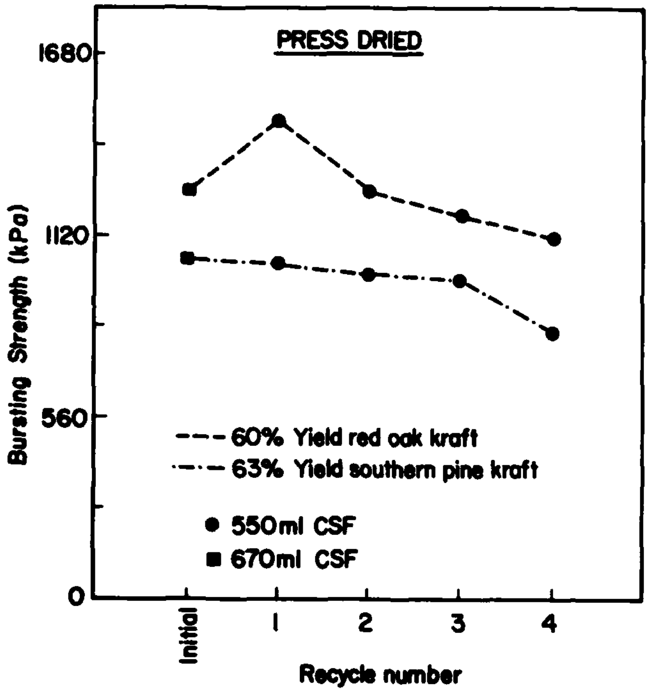

Figure 2.--Bursting strength of press-dried handsheets made from 63%-yield southern pine and 60%-yield southern red oak kraft pulps. Basis weight of 205 g/m². (ML83 5438)

preceded by refining, there is a continuous loss in strength. Therefore, to achieve the full benefits of press drying, it appears that recycled fiber has to be refined after each recycle.

The effects of press drying a 60% yield southern red oak kraft fiber after recycling are essentially similar to the effect of press-drying southern pine fiber. A major difference, however, is the red oak fiber used in this study is much more responsive to press drying than the southern pine fiber. This is illustrated in figure 2.

A further aspect of the handsheet study was to determine the effects of press drying on "clean" recycled old corrugated material. With the exception of tear strength, all other properties of press-dried recycled old corrugated had superior strength properties compared to conventionally dried Tappi handsheets.

Feasibility of Making Linerboard From 100% Recycled Fiber

This portion of the study involved making linerboard on the FPL pilot press dryer from both "clean" and "contaminated" recycled old corrugated material. The "clean" material was the same material used in the handsheet study. The "contaminated" material was a commercial secondary fiber furnish which had been cleaned but contained an abundance of contaminants.

The response of the "clean" old corrugated to press drying was very positive. In fact, the overall physical properties of press-dried recycled, with the exception of tearing strength, are better than a conventionally dried linerboard made from virgin southern pine kraft fiber (fig. 3).

The best press-dried linerboard made from the "contaminated" secondary fiber (without rosin size) is weaker than the press-dried linerboard from "clean" corrugated, but approaches the overall strength of the liner made from virgin pine fiber (fig. 4). The effect of sizing on strength properties is mixed. Sizing had little effect on the "clean" stock furnish. However, addition of rosin size to the "contaminated" furnish appeared to have a slight negative effect on strength. Both the "clean" and "contaminated" stock were responsive to refining. With the exception of tearing strength, refining increased the strength of press-dried linerboard made from recycled fiber.

Press drying produced a significant improvement in the difference between machine direction (MD) and cross-machine direction (CD) tensile strength, i.e., MD to CD ratio (figs. 3C,4C). For instance, in the conventionally dried linerboard, the ratio of MD to CD was, in all cases, at least 2:1. With press drying, this ratio was improved to 1.5:1 and, at worst 1.7:1. This improvement in sheet squareness is a result of uniform X-Y restraint across the sheet during drying.

Properties of the Combined Board and Boxes Made From Press-Dried Recycled Fiber

The properties of the combined board made from the "clean" stock press-dried components essentially equaled or exceeded those of the virgin, commercial board. Press drying effectively eliminates the problem of scoreline fractures. Of particular interest is the beneficial effect of press drying on short column compression, especially at high humidity (fig. 5). At 90% relative humidity (RH), the combined board made from all press-dried components is nearly as strong in compression as the commercial board at 30% RH and is stronger than the commercial board at 50% RH.

The combined board made from press-dried components did show a slight loss in bursting strength (fig. 6). However, the press-dried combined board made from the "clean" material still meets the standards of acceptable burst level, i.e., Rule 41. Recycle of the virgin board followed by conventional drying resulted in a marked reduction in bursting strength.

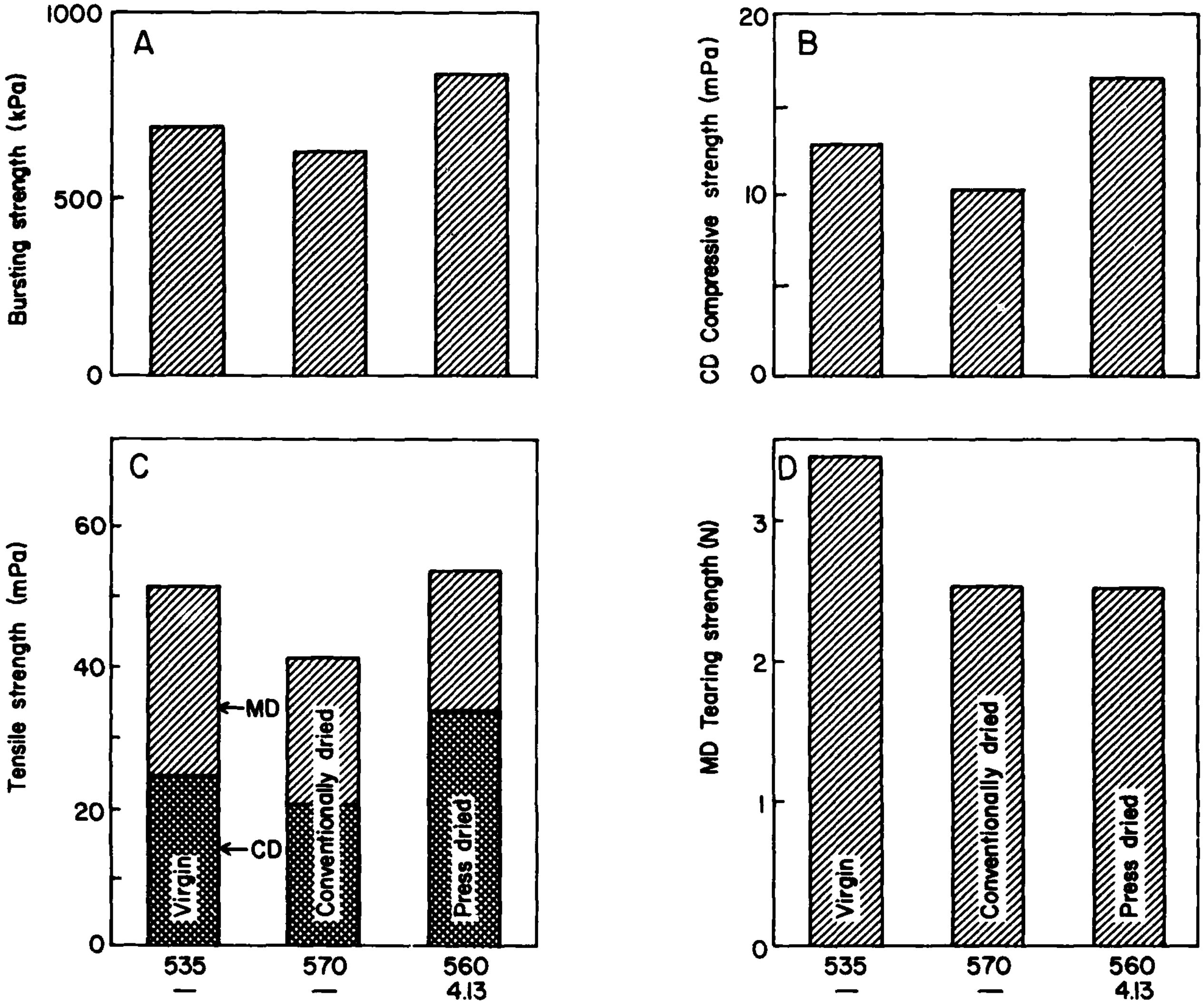

Figure 3.--Physical properties of machine-made linerboards from virgin southern pine kraft fiber and recycled "clean" old corrugated dried by conventional drying, and press-dried linerboard from recycled "clean" old corrugated. Rosin size added (0.2%). Designations on the abscissa are: top--Canadian Standard freeness (ml); bottom--pressing nip pressure (MPa). Basis weight of 205 g/m². (A) Bursting strength, (B) CD compressive strength, (C) Tensile strength, and (D) MD tearing strength (CD = cross-machine direction; MD = machine direction). (ML83 5439)

Top-to-bottom compressive strength of boxes made from all press-dried recycled components was equal to or higher than the strength of boxes made from virgin components. However, impact failure height was somewhat lower for press-dried boxes.

The results of this study indicate that press drying is a viable means of overcoming the obstacles to increasing the use of recycled fiber for products requiring high strength, e.g., linerboard.

LITERATURE CITED

Horn, Richard A., and Vance C. Setterholm. 1983. Continuous on-line press drying of high-yield oak fiber for linerboard. Tappi 66(6):59-62.

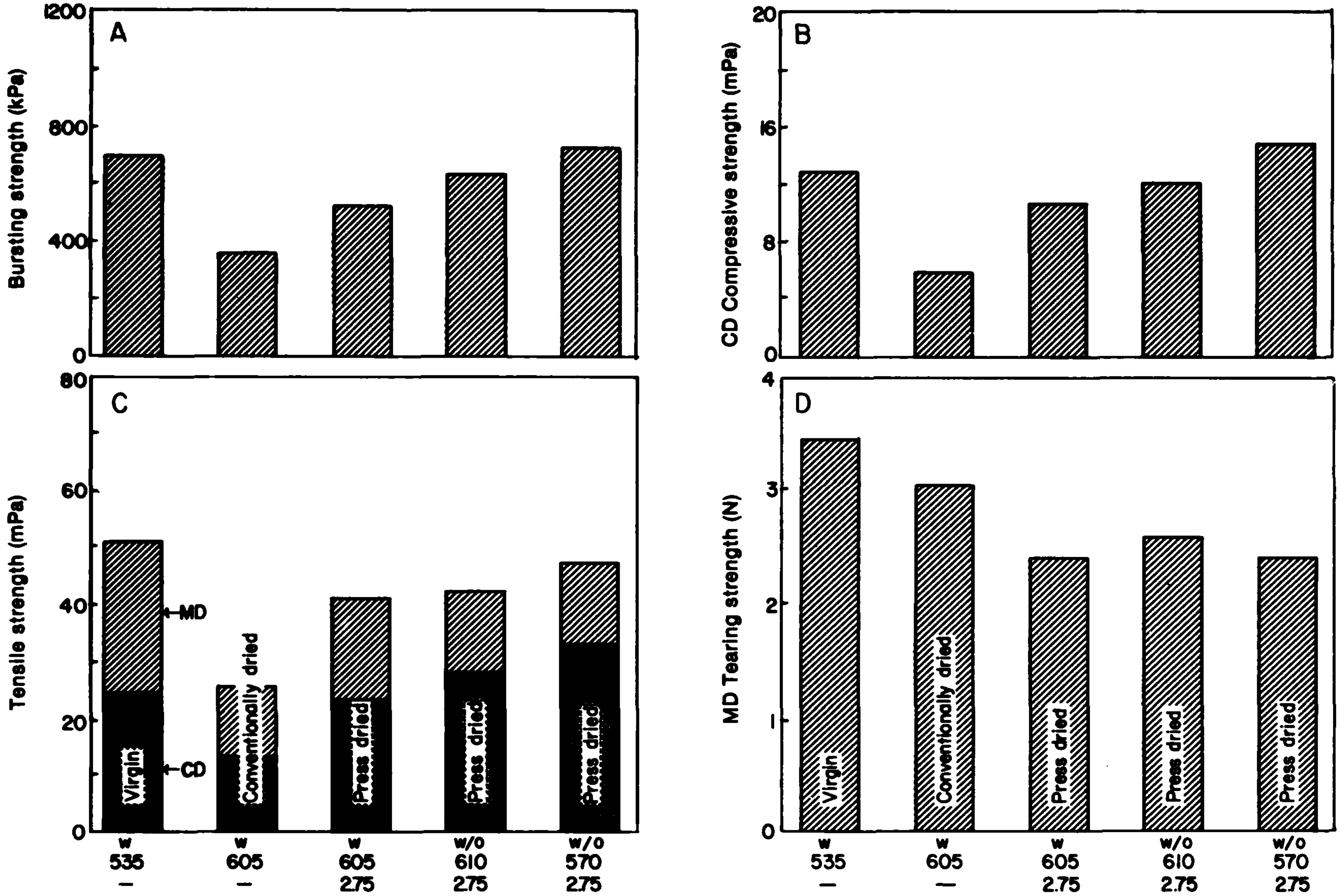

Figure 4.--Physical properties of machine-made linerboards from virgin southern pine kraft fiber and recycled "contaminated" secondary fiber dried by conventional drying, and press-dried linerboard from recycled "contaminated" secondary fiber. Designations on the abscissa are: top--0.2% rosin size, (w) with and (w/o) without; center--Canadian Standard freeness (ml); and bottom--pressing nip pressure (mPa). Basis weight of 205 g/m^2. (A) Bursting strength, (B) CD compressive strength, (C) Tensile strength, and (D) MD tearing strength (CD = cross-machine direction; MD = machine direction). (ML83 5440)

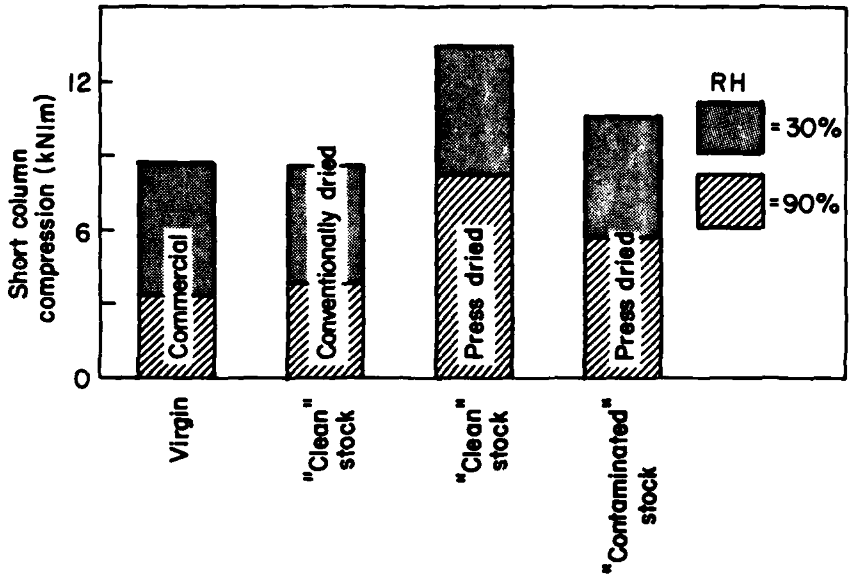

Figure 5.--Short column compression strength of combined boards made from press-dried and commercial components. (ML83 5442)

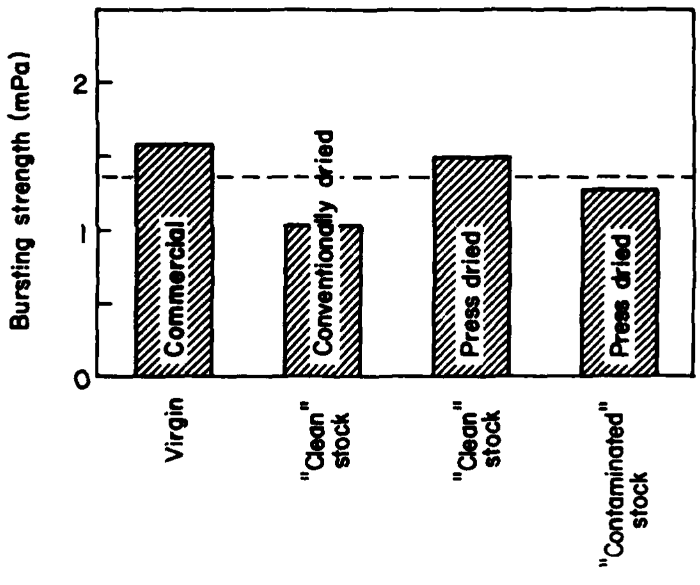

Figure 6.--Bursting strength of combined boards made from press-dried and commercial components. The dotted line represents acceptable level of bursting strength for combined boards of 1.38 mPa. (ML83 5441)

CONVAC PRESS DRYING AS A POSSIBLE PRODUCTION PROCESS[1]

Jukka Lehtinen[2]

INTRODUCTION

The basic principle of Convac drying has been explained by Lehtinen (1980). Figure 1 is shown here for a rapid review.

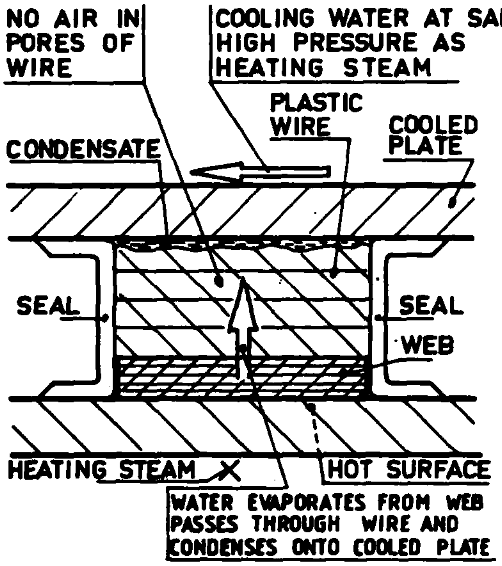

Figure 1.--Basic process in Convac drying

The cooled platen temperature largely determines the pressure of the vapor in the pores of the wire. Therefore, if the cooled platen temperature is kept at a low value, say about 20°C, the vapor in the pores of the wire is at a low pressure (ab. 2...10 kPa). If the pressure outside the platens is the atmospheric, the wire presses the web against the heated platen with a pressing effect of almost an atmosphere. The resulting drying rate is very high.

Figure 2 here is from Lehtinen (1980). Ahrens and Journeaux (1982) have obtained experimental results roughly compatible with those shown in fig. 2, though the shape of their curves, due to a more suitable apparatus and better measuring technique is more realistic: the curves curve up on the left, and to the right they approach a horizontal asymptote.

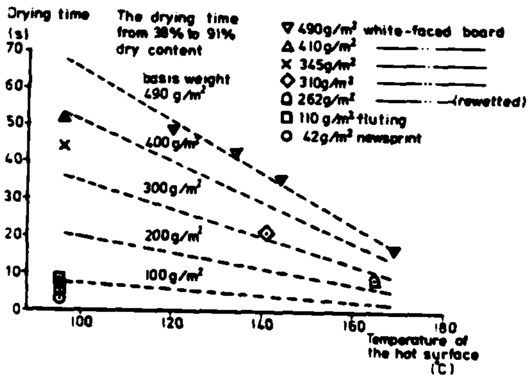

Figure 2.--Convac drying time for various grades as function of surface temperature.

It was shown by Lehtinen (1982) that a possibly very useful feature of Convac drying is the fact that the drying rate is little dependent on the cooled platen temperature. This was explained as being probably due to two factors principally:

1. The specific volume of the vapor leaving the web is roughly determined by the cooled platen temperature. Therefore, with an increased temperature at the cooled platen, the vapor passing through the wire experiences a smaller pressure drop, and the evaporation pressure and temper-

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[1] Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2] Consultant to Tampella Ltd., Tampere, Finland

ature do not increase much.

2. Nevertheless, with an increased cooled platen temperature, the average temperature in the portions of the web transferring heat from the platen to the points of evaporation increases somewhat. This means a lower viscosity and surface tension for the capillary water. As the spreading of capillary water and Marangoni convection probably play major roles in the heat transfer, the effective thermal resistance of the web decreases. Ahrens (1982) has studied the temperature and moisture distribution in the web theoretically, neglecting, however, Marangoni convection. The permeability value used by him is probably not realistic.

The experimental results suggest that the Convac process can well be operated with the temperature difference between the heated and cooled platens at 30...40°C. Then the drying rate will most likely not be more than 50% lower than that given in figure 2. (the results for wich were obtained with the cooled platen at about 20°C). In this respect there seem to be only a few precise measurements by Lehtinen (1982), and a number of rough observations.

The next step in the development of Convac drying is to increase the pressure acting on the platens from the outside to a level of several bars, and to raise the cooled platen temperature to a value at or above 100°C. Lehtinen (1982) determined that the temperature of the wire-web interface is typically 25...55° above the temperature of the cooling water. This means that if the cooling water temperature is $\geq$ 80°C, every part of the web is at temperature $>$ 100°C. If the pressure external to the platens is a few bars or more, we then have almost an ideal press drying condition for the web. The only notable departures from ideality are then the temperature variation within the web and the necessarily marking imprint that the wire leaves on one side of the web.

The drying rate has been observated to increase, with the increasing Z-directional pressing effect in press drying, from the values shown in figure 2. Roughly, the increase has been observed to be about 20...30% when the Z-pressing pressure goes to 0,5 MPa.

The heating medium can suitably be saturated steam and the cooling medium water at the same pressure as that steam, but at a temperature perhaps 30...40°C lower. The vapor condensing on the inside surface of the cooled platen will then have a temperature $>$ 100°C. This means that the success of the edge sealing will not be vital to the success of the press drying operation: a leaking seal means only the loss of some steam, and a somewhat lowered web temperature (but that temperature will still be above 100°C throughout the web).

THE PROPOSED, PREFERRED, CONVAC PRESS DRYING MACHINE

A production device, figure 3, was proposed in Lehtinen (1982). The heated and cooled platens of the static device are replaced by steel bands running at the speed of the machine. In the drying zone the two bands, which sandwich the web and the wire between them, are compressed between the heating steam chest and the cooling water chest. The chests are open toward the running bands, and there must be a seal around the edge of a chest with the band sliding on that seal. There will be leakage past the chest edge seals, but it will be fairly easy to contain the leakage in the spaces inside the band loops.

The wire and the web can be purged of air by passing them, before the drying zone, through a chamber where steam at slighly higher than atmospheric pressure is blown through them.

The process can be run as a single-stage process, heat-pumping the latent heat that flows into the cooling water back into the heating steam. No major external steam supply is needed for such a drying section. According to calculations from Lehtinen (1982), the total electric power consumption for heat-pumping for the whole drying section can be held in the range 90...150 kWh/ton of dry product. This means a drying section energy cost of about \$ 4...7 per ton of product (at 4,0 ¢/kWh). These are very low figures compared with what is being paid today with external steam generation.

The special feature of the Convac process - that the process may be run at a very high drying rate but with a small temperature difference between the heated and the cooled platens - makes possible also operation in cascade series, figure 3. The first stage receives saturated steam from an outside source, typically at a pressure of 0,8...1,0 MPa. The cooling water in its chest is at this pressure, but at a temperature perhaps 40°C below that of the steam. The cooling water is passed through a pressure reducing valve to a cyclone flash evaporator, where part of the water evaporates. The temperature of the remaining water drops by about 10°C, and this water, replenished with fresh water, is fed back to the cooling water chest. The evaporated steam leaves the flash unit at about 0.4...0.6 MPa pressure and goes to the second drying unit.

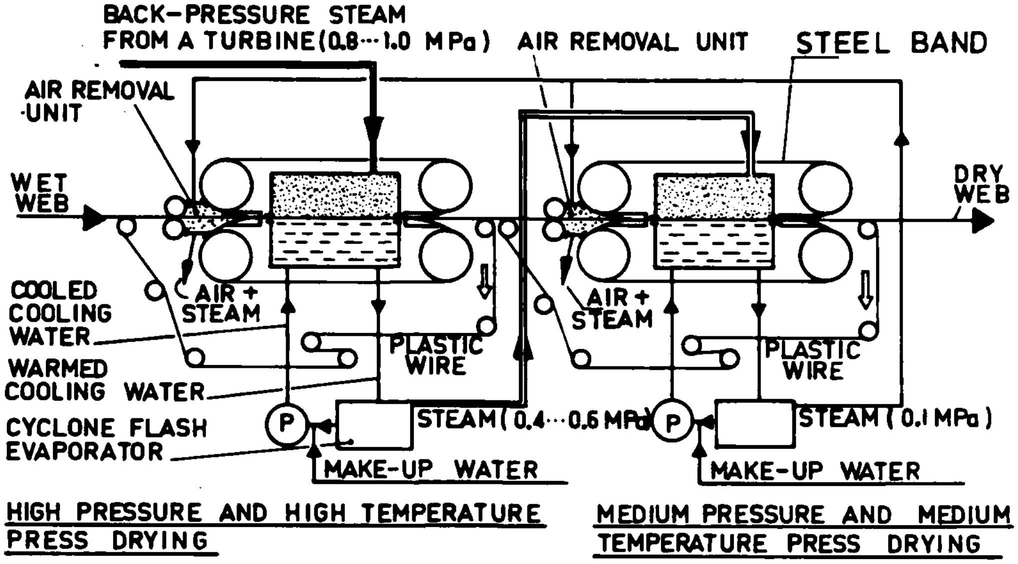

Figure 3.--Proposed two-stage cascade press drying Convac arrangement

This steam may suffice for the heating steam needed for that unit, or fresh steam from the outside may also be needed. In any case, the second unit also operates under press drying conditions: the web temperature $>$ 100°C throughout, and the Z-directional pressure about 0.4...0.6 MPa.

The cooling water leaving the second unit (at about 105...110°C) may also be flashed to produce steam at about 100°C for the two air purging units of the drying section. Alternatively, the air purging may be done by pumping air from the purging chambers, holding a very low pressure in those chambers, or by a combination of using a fairly low pressure in those chambers and blowing low pressure steam through the web and the wire.

It is advisable to have the steel band loops inside closed hoods (not shown in figure 3) in order not to lose heat from the bands during their return run. This is recommendable also from the viewpoint of safety: if a fatigue failure should occur in the bands, the consequences would be fearful without safety precautions.

If the side seals function properly it is possible to recover the heat in the first stage at a sufficiently high temperature to be able to feed the second stage with steam of high enough pressure as to have press drying in the second stage. It is not possible to discuss here the design of the side seals further - it is believed, however, that viable alternatives are available.

With steel bands, one can avoid excessive fatigue by avoiding bending radii smaller than about 600 times the band thickness. According to a well-known manufacturer, narrow steel bands have been run successfully at about twice the speed that would be encountered in a paper machine, and about 6 m wide bands have also been run successfully, but only at very slow speeds.

THE CONVAC PRESS DRYING PROCESS COMPARED WITH OTHER POSSIBLE PRESS DRYING PROCESSES

The possibility of doing press drying by passing the wet web between fine metal wires, with these together passing through a highly loaded nip between two very hot metal cylinders, has been frequently brought forth. One could have many of the nips in series, and in addition, compress the web against a rotating hot cylinder with a tensioned wire or band in between these nips. A great difficulty in the multiple cylinder nip process referred to above is the fact that in fast paper machines the web passes through a nip in a few milliseconds. The web should then be preheated. It is normally not possible to preheat the web to temperatures above 100°C, however. Cold pressing, followed by light, but longer-time pressing as a high temperature has been used seccessfully (Setterholm and Benson 1977), though.

The experimental results comparing the web strength values obtained by multistage short-duration hot pressing with those obtained by single-stage pressing at the same platen temperatures and pressures indicate that the multistage press drying route cannot, as a rule, produce a web with as high strength properties as the single-stage pressing route (Yang et al 1979). It has been shown by Byrd (1979 b) that the time needed for the hemicelluloses to flow freely in a contact drying situation is of the order of 1 s, while the corresponding time for lignin is of the order of 15 s. Since it is the softened hemicelluloses that account for most of the bond strength improvement resulting from press drying (Horn 1979), and since the flow of lignin also helps the hemicellulose to flow more extensively (Back and Swenson 1981), and since in press drying the softening of cellulose and lignin also helps to deform and mold the stiff fibers of high lignin pulp (Salmén and Back 1979) to form a denser web with more bonding area between the softened fibers (Yang et al 1979), it seems reasonable to expect that single-stage press drying lasting for several seconds would yield the best strength values, especially for high lignin pulps. This would, then, seem to be the strongest feature in favor of the Convac press drying arrangement of figure 3.

The energy economy of the cascade series arrangement shown in figure 3 is also very fine. The consumption of steam for the whole drying section would be roughly half of what it is in the best conventional sections. On the other hand, the press drying processes relying on very hot press nips would most likely be wasteful of heat, and would use high temperature steam, reducing the cogeneration advantage. The Convac press drying arrangement would also seem to offer a possibility for heat pumping, dispensing with the need for external steam for the drying process. Heat pumping has not been considered economically viable with other drying methods.

The Convac press drying process would also appear to offer very great versatility of drying conditions (temperatures, pressures, and drying times). The surface quality could also be regulated and raised to a high level (Lehtinen 1980).

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Economics

ECONOMICS OF INVESTMENT IN PRESS DRYING FOR KRAFT LINERBOARD[1]

Peter J. Ince[2]

This report includes estimates of capital costs and evaluates the economics of investment in press drying for producing kraft linerboard. In a new linerboard mill, press drying offers an overall rate of return on investment estimated at 1-3/4 times that of a conventional process. Conversion of an existing linerboard mill to press drying offers an estimated rate of return that is 2-1/2 times that of investment in a new conventional mill.

Investment in New Mills

It would require about 10% less capital to build a new linerboard mill with press drying than to build a new conventional mill. Capital investment estimates for hypothetical new linerboard mills with conventional and press-drying processes are shown in table 1. Estimates for the conventional 1,270-metric-ton-per-day mill were based on information provided by The Rust Engineering Company. Estimates for the same capacity mill with press drying were developed at the Forest Products Laboratory (FPL). Press drying reduces capital requirements in the wood preparation and digester areas because of higher-yield pulping, and lower wood requirements. Similarly, capital requirements in evaporators, recovery boiler, and chemical recovery areas are reduced with press drying because of higher yield and less black liquor per ton of pulp. Capital requirements for the power boiler are reduced because of reduced overall energy requirements. Capital requirements for stock preparation are reduced because of reduced fiber refining requirements with press drying. The capital cost estimate for the press-drying linerboard machine is based on Bob Daane's original concept of a commercial press dryer.[3]

Table 1.--Capital investment estimates for hypothetical new 1,270-metric-ton-per-day linerboard mills, conventional and press-drying process

Mill area	Conventional process	Press-drying process
	- - - - Dollars - - - -	
Land and site development	10,000,000	10,000,000
Wood preparation area	45,000,000	41,700,000
Digester area	41,000,000	33,900,000
Washing and refining	24,000,000	24,000,000
Stock preparation	11,000,000	8,100,000
Linerboard machine	120,000,000	123,000,000
Additives area	2,000,000	1,300,000
Finishing and shipping	4,000,000	4,000,000
Water supply system	8,700,000	8,700,000
Waste disposal	12,000,000	12,000,000
Electric and cogeneration	20,000,000	20,000,000
Power boiler	40,000,000	26,800,000
Coal handling	12,000,000	12,000,000
Recovery boiler	58,500,000	44,500,000
Evaporators	12,600,000	9,500,000
Recausticizing and kiln	18,000,000	13,600,000
Miscellaneous	30,000,000	30,000,000
Working capital	30,000,000	30,000,000
Total capital investment	498,800,000	453,100,000

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[1]Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2]Peter J. Ince is a Research Forester, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

[3]Daane, Robert A. 1982. Conceptual design of a commercial scale press drying system: Final report. Prepared for the USDA Forest Service, Forest Products Laboratory, under Research Agreement FP-80-0242. On file at Forest Products Laboratory, Madison, Wis. (draft).

Converting Old Mills

Installing press drying at an existing mill is potentially more economical than installing press drying in a new mill. Installation of press drying at an existing mill is estimated to cost only about one-fourth as much as installation of a complete new mill. Table 2 shows estimated net investment cost, including adjustment for 6 months of downtime, for installation of press drying at a hypothetical existing 1,270-metric-ton-per-day linerboard mill. Again, the capital cost of the press dryer is based on Daane's concept. Cost of the press dryer is lower at an existing mill than at a new mill because of assumed use of some existing facilities.

Table 2.--Estimated net investment cost for conversion to press drying of an existing 1,270-metric-ton-per-day conventional linerboard mill

Capital investment in new press-drying equipment	$ 78,000,000
Old equipment salvage value	(10,000,000)
Revenue and cost adjustments for downtime during estimated 6-month installation period:	
Lost product sales revenues	73,500,000
Labor costs	7,000,000
Administrative overhead	3,300,000
Other variable costs not incurred	(31,300,000)
Net investment cost total	$120,500,00

Cash Flow Analysis

Cash flow analysis is used to investigate the investment opportunity in press drying at new and older existing mills. Annual cash flow estimates for the hypothetical 1,270-metric-ton-per-day mills are shown in table 3 for conventional and press-drying processes at new and at older existing mills. Annual operating costs are based on estimates discussed in my previous report on process economics.[4] Cash flow analysis is based on the assumptions given in table 4. Results of the cash flow analysis are summarized in table 5. Results show that press drying offers an outstanding improvement in linerboard mill investment opportunities relative to the conventional process.

[4]Ince, Peter J. 1983. Process economics of press drying for kraft linerboard. Press Drying Conference, 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

Sensitivity Analysis

Finally, sensitivity analysis shows the effects of changes in key variables on the investment criteria for both the conventional and the press drying investments at new mills. Figure 1 shows the effects of changes in key variables on estimated rate of return and present net worth for the investment in a new linerboard mill with press drying. Figure 2 shows the

Table 3.--Annual cash flow estimates for hypothetical 1,270-metric-ton-per-day linerboard mills, new and older existing mill with conventional and press-drying processes

	Annual cash flows ($1,000/year)	
	Conventional	Press drying
NEW LINERBOARD MILLS		
Revenues		
Linerboard	144,130	144,130
Tall oil soap	2,562	0
Turpentine	301	0
	146,993	144,130
Costs		
Pulpwood	40,636	25,792
Labor	14,035	14,035
Fuels	12,260	4,644
Electricity	4,305	4,796
Chemicals and additives	5,064	3,025
Supplies	1,402	1,839
Overhead	6,700	6,700
	84,402	60,831
OLDER EXISTING MILLS		
Revenues		
Linerboard	144,130	144,130
Tall oil soap	1,254	0
Turpentine	1,544	0
	146,928	144,130
Costs		
Pulpwood	41,709	25,792
Labor	14,035	14,035
Fuels	16,488	5,585
Electricity	3,644	4,510
Chemicals and additives	8,826	4,862
Supplies	1,402	1,839
Overhead	6,700	6,700
	92,804	63,323

effects of changes in key variables on estimated rate of return and present net worth for the investment in a new mill without press drying (conventional process). In both new-mill examples (press drying and conventional) the estimated investment criteria, rate of return, and present net worth change with change in key variable assumptions. Some variables are shown to have a greater influence than others. However, it is also shown that press drying has a considerable economic advantage over the conventional process over a wide range of hypothetical assumptions.

Conclusions

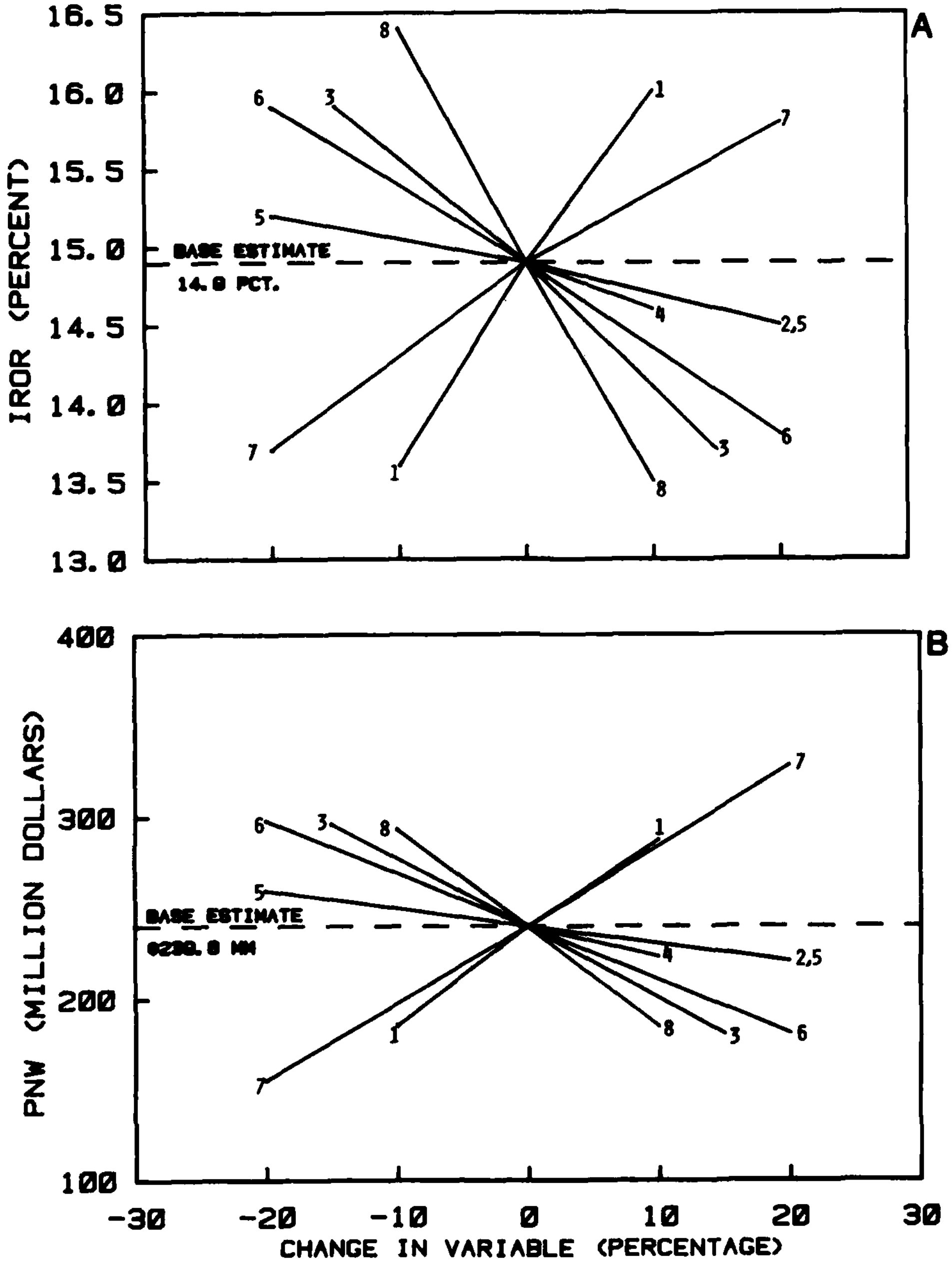
Press drying offers considerable economic advantages over a conventional process for producing kraft linerboard. Not only does press drying offer considerable savings in process variable costs, but it also offers large savings in capital investment requirements for a new mill. Press drying is also an attractive investment for conversion of an existing mill. Adoption of the press-drying process offers 1-3/4 times the rate of return on investment in a new linerboard mill and an even higher rate of return on investment at an existing mill.

Table 4.--Estimates and assumptions used in the cash flow analyses of press-drying and conventional linerboard mills

Planning period from mill start up	20 years
Time of initial capital investment	January 1983
Time of start up for new mills	July 1984
Time of start up for conversion to press drying	July 1983
Annual income tax rate	40%
Annual discount rate on after-tax net cash flows (for PNW calculations)	10%
Investment tax credit	10%
Annual inflation rate on general cash flows	8%
Annual inflation rate on fossil fuel costs	12%
Depreciation schedule	1983 A.C.R.S.
Financing arrangement	100% equity
Ratio of 15-year to 5-year property in total capital investment (excludes working capital)	1:10

Table 5.--Results of cash flow analyses of investments in new 1,270-metric-ton-per-day linerboard mills using conventional technology and press-drying technology, and in conversion of existing 1,270-metric-ton-per-day mill to press drying

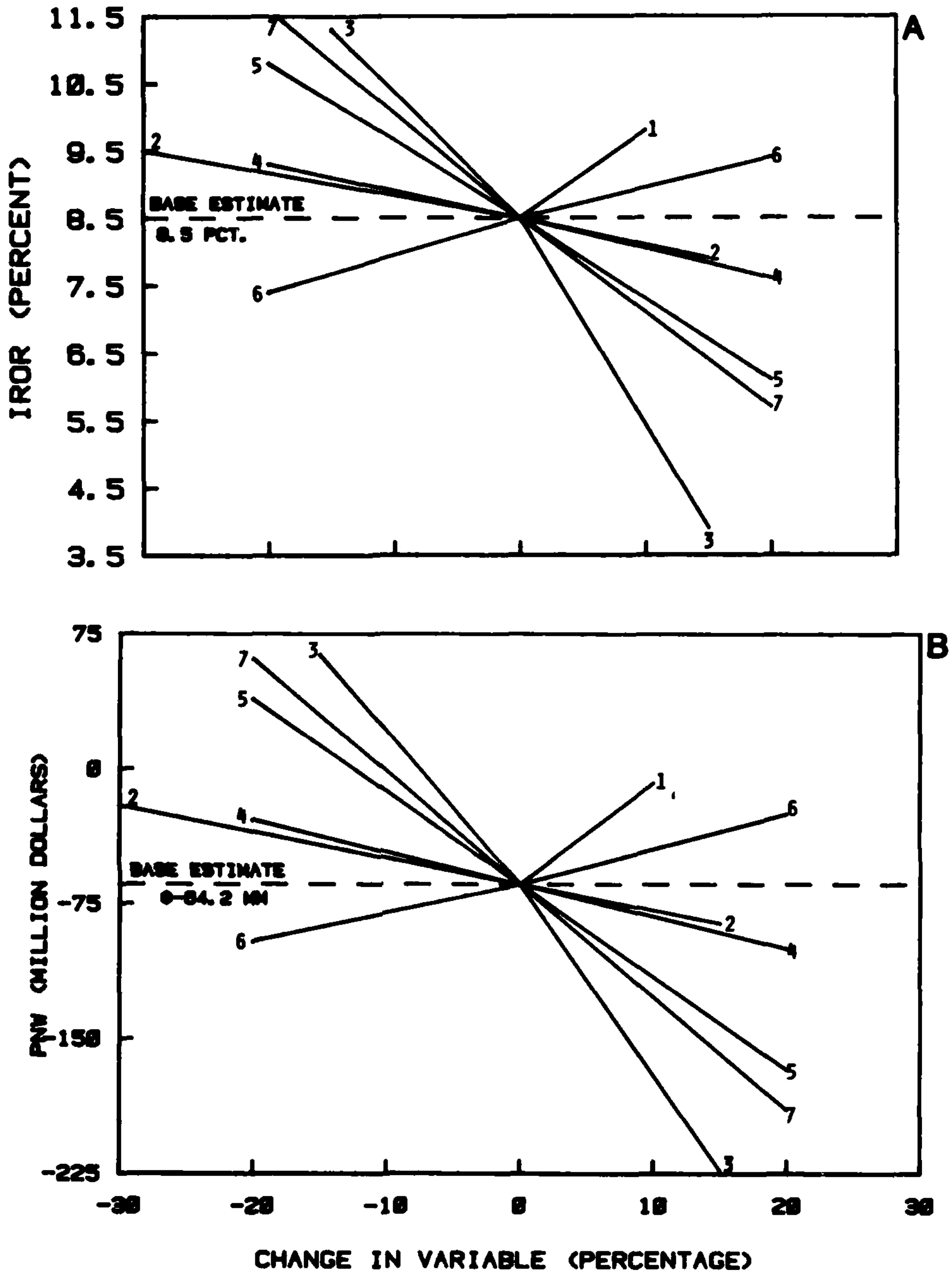
	Net investment required (January 1983)	Investment criteria (after taxes): Present net worth (10% i)	Investment criteria (after taxes): Internal rate of return	Payback period based on after-tax net cash flows	Before-tax rate of return
	- - - - - Dollars	- - - - -	(%)	(Yr)	
NEW MILLS					
New conventional mill	498,800,000	-64,172,000	8.5	10.6	11.7
New press-drying mill	453,100,000	239,792,000	14.9	6.9	18.5
EXISTING MILL					
Conversion of older existing mill to press drying	120,500,000	167,063,000	20.8	5.6	26.3



VARIABLE CODE

1 PULP YIELD (BASE=65 PERCENT)
2 PERCENT SOFTWOOD FURNISH (BASE=0 PERCENT)
3 TOTAL PROCESS ENERGY REQUIREMENTS (BASE=100 PERCENT)
4 MOISTURE CONTENT INTO DRYERS (BASE=45 PERCENT)
5 FOSSIL FUEL & ELECTRICITY PRICES (BASE=100 PERCENT)
6 PULPWOOD PRICES (BASE=100 PERCENT)
7 PRODUCTION VOLUME (BASE=100 PERCENT=1270 TPD)
8 TOTAL INVESTMENT REQUIRED (BASE=100 PERCENT=$453.7 MILLION)

Figure 1.--Sensitivity of (A) estimated internal rate of return (IROR) and (B) estimated present net worth (PNW) to percentage change in key variables for an investment in a hypothetical new 1,270-metric-ton-per-day linerboard mill with press-drying process. (ML83 5422)



VARIABLE CODE

1 PULP YIELD (BASE=53.5 PERCENT)
2 PERCENT SOFTWOOD FURNISH (BASE=85 PERCENT)
3 TOTAL PROCESS ENERGY REQUIREMENTS (BASE=100 PERCENT)
4 FOSSIL FUEL & ELECTRICITY PRICES (BASE=100 PERCENT)
5 PULPWOOD PRICES (BASE=100 PERCENT)
6 PRODUCTION VOLUME (BASE=100 PERCENT=1270 TPD)
7 TOTAL INVESTMENT REQUIRED
(BASE=100 PERCENT=$490.0 MILLION)

Figure 2.--Sensitivity of (A) estimated internal rate of return (IROR) and (B) estimated present worth (PNW) to percentage change in key variables for an investment in a hypothetical new 1,270-metric-ton-per-day liner-board mill with a conventional process. (ML83 5423)

PROCESS ECONOMICS OF PRESS DRYING FOR KRAFT LINERBOARD[1]

Peter J. Ince[2]

INTRODUCTION

Press drying should offer major economic advantages in producing kraft linerboard. In this study, I compared the process economics of a hypothetical new conventional linerboard mill with a hypothetical new press-dry linerboard mill. Analysis indicates that press drying would produce the following advantages:

(1) An estimated 35% to 40% savings in wood raw material costs.

(2) 40% to 45% savings in total energy costs.

(3) 30% overall savings in variable costs.

(4) An estimated 30% improvement in profit contribution.

The projected performance of a hypothetical older mill, compared with its performance if converted to press drying in the papermaking section, showed even greater advantages.

These potential economic advantages come from efficiencies in the press-drying process: Laboratory research shows that press drying permits use of up to 100% hardwood fiber in linerboard as a substitute for softwood fiber, that press drying permits use of higher yield pulp (e.g. 65% yield or higher versus conventional yield of 50% to 55%), and that press drying permits lower moisture content in the sheet as it enters thermal drying (e.g., as low as 45% moisture content versus conventional 60% to 62%).

METHODS

Process Assumptions

The economic advantages reported in this paper are based on detailed analysis of the potential impact of press drying on an overall linerboard production process, from wood preparation through pulping and papermaking. Process design data for a hypothetical new conventional linerboard mill were provided by The Rust Engineering Company. Comparable data for a press-drying process were estimated at the Forest Products Laboratory, based on laboratory research studies. Table 1 shows process data estimates for the conventional and press-drying processes. The key differences are as follows:

(1) Press drying uses 100% hardwood fiber versus only 15% hardwood fiber for conventional linerboard furnish.

(2) Press drying uses pulp at 65% yield versus only 53.5% yield for conventional.

(3) Press drying has the sheet enter thermal drying at 45% moisture content drying versus 60% for conventional drying. The estimated effects of these differences include a 39% advantage in overall process energy requirements, as shown in table 2. The estimated material requirements for press drying are also considerably different from those for the conventional mill, as shown in table 3.

Data process assumptions were modified to reflect a hypothetical older existing mill with less efficient conventional process, including higher sheet additive requirements, less efficient pulping process, less efficient sheet drying, and greater dependency on softwood fiber.

Value Assumptions

Explaining these results in economic terms requires data assumptions on the values of material inputs and product outputs. Data assumptions on values of inputs and outputs were obtained from public information sources, trade journals, and price reporters. The value assumptions used in this analysis are shown in table 4.

Sensitivity Analysis

The cost estimates for a new mill were also subjected to sensitivity analysis to determine the effect of changes in key assumptions. The sensitivity analysis varies the key assumptions of pulp yield, percent softwood furnish, pulpwood value, total energy requirements, and moisture content of the sheet entering the dryers.

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[1]Extended abstract of a paper presented at Press Dry Conference 1983 [Forest Products Laboratory, Madison, Wis., September 7-9, 1983].

[2]Peter J. Ince is a Research Forester, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

RESULTS

New Mill Comparison

The variable costs of producing one metric ton of linerboard at a hypothetical new mill are estimated to be about $170 with the conventional process, versus only about $120 with the press-drying process. Estimated variable costs by item are shown for comparison in figure 1. No effect on labor costs were considered here, although press drying would possibly afford lower overall labor requirements because of higher pulp yield, less wood requirements, etc. When revenues are considered, press drying is estimated to offer a higher profit contribution:

Item	Conventional	Press drying
	($/metric ton linerboard)	
Revenues		
Linerboard	320.00	320.00
Naval stores	6.36	0
Total variable costs	172.31	120.06
Profit contribution	154.05	199.94

This analysis concludes that press drying at a new linerboard mill offers a net savings of at least $45 per metric of linerboard, or a 30% improvement in profit contribution, relative to a conventional process.

Table 1.--Data estimates for conventional and press-drying linerboard processes

Item	Conventional	Press drying
WOOD RAW MATERIAL DATA (DRY WEIGHT BASIS)		
Softwood ratio of total wood furnish to digester (%)	85	--
Hardwood ratio of total wood furnish to digester (%)	15	100
Roundwood (vs. chip) fraction of purchased pulpwood (%)	50	75
Fraction of pulpwood removed as bark and fines (%)	11.3	12.7
PULPING DATA		
Pulp yield, based on ovendry wood weight (%)	53.5	65
Active alkali, as Na_2O based on ovendry wood weight (%)	14.5	10.9
Black liquor solids, tons per dry ton of pulp (ton/ton)	1.31	.81
Turpentine recovery, liters per dry metric ton of wood furnish (liter/ton)	2.3	--
Soap recovery, kilograms per dry metric ton of wood furnish (kilogram/ton)	41.2	--
PAPERMAKING DATA		
Production volume (linerboard) (metric tons/day)	1,270	1,270
Additives (kg/metric ton product)		
Alum	10	5
Acid	10.5	5.2
Rosin	.75	.75
Other stock additives	1.3	1.3
Moisture content of sheet (total weight basis)		
Into dryers (%)	60	45
Out of dryers (%)	6	4
Relative energy efficiency in drying (kilograms of steam required to evaporate one kilogram of moisture in sheet)	1.47	1.28

Table 2.--Estimated overall process energy requirements for conventional and press drying processes

Item	Conventional	Press drying
Net steam energy requirements (gigajoules/metric ton linerboard)		
Paper machine dryers	5.4	2.5
Black liquor evaporators, concentrators	4.3	2.7
Pulping process	2.8	2.2
Chemical recovery	2.2	1.5
Other, miscellaneous	6.8	3.7
Total	21.5	12.6
Electric power requirements (kilowatt-hours/metric ton linerboard)		
Wood preparation area	65	60
Digester area	80	70
Washing, refining, stock preparation	275	200
Paper machine, finishing area	130	65
Water and air supply, waste system	85	85
Power boiler, fuel handling	75	35
Black liquor recovery, recausticizing	75	50
Other, miscellaneous	75	75
Total (kwh)	860	640
(gigajoules)	(3.1)	(2.3)
Total process energy requirements (gigajoules/metric ton linerboard)	24.6	14.9

Old Mill Comparison

Variable costs estimated for the older existing mill totaled over $190 per metric ton of linerboard. However, if the mill is converted to press drying in the papermaking section and if fiber furnish is switched to hardwood, estimated variable costs drop to about $125 per metric ton of linerboard, a savings of $65 over the conventional process. Variable costs estimated for conventional and press-drying processes at the hypothetical older existing mill are shown in figure 2. The estimated improvement in profit contribution at the older existing mill is about $60 per metric ton of linerboard.

Sensitivity Test

The results of the sensitivity test are shown in figures 3 and 4. Figure 3 shows how total variable cost for a new conventional process is estimated to change with percentage changes in key assumptions. Figure 4 shows similarly how the total variable cost for the press-drying process is estimated to change with percentage changes in key assumptions. Results of the sensitivity analysis show that press drying offers economic advantages across a wide range of data assumptions.

CONCLUSIONS

The hypothesis that press-drying offers major economic advantages in producing kraft linerboard, relative to a conventional process, is supported by a detailed analysis of process variables from wood preparation through pulping and papermaking.

Press drying offers a $45 to $60 per metric ton advantage over conventional processes for producing kraft linerboard. The advantage varies depending on whether press drying is compared to a conventional process at a new or older existing mill. The economic advantage of the press-drying process derives primarily from use of higher yield pulp, more efficient drying, and use of lower value fiber (e.g. hardwood).

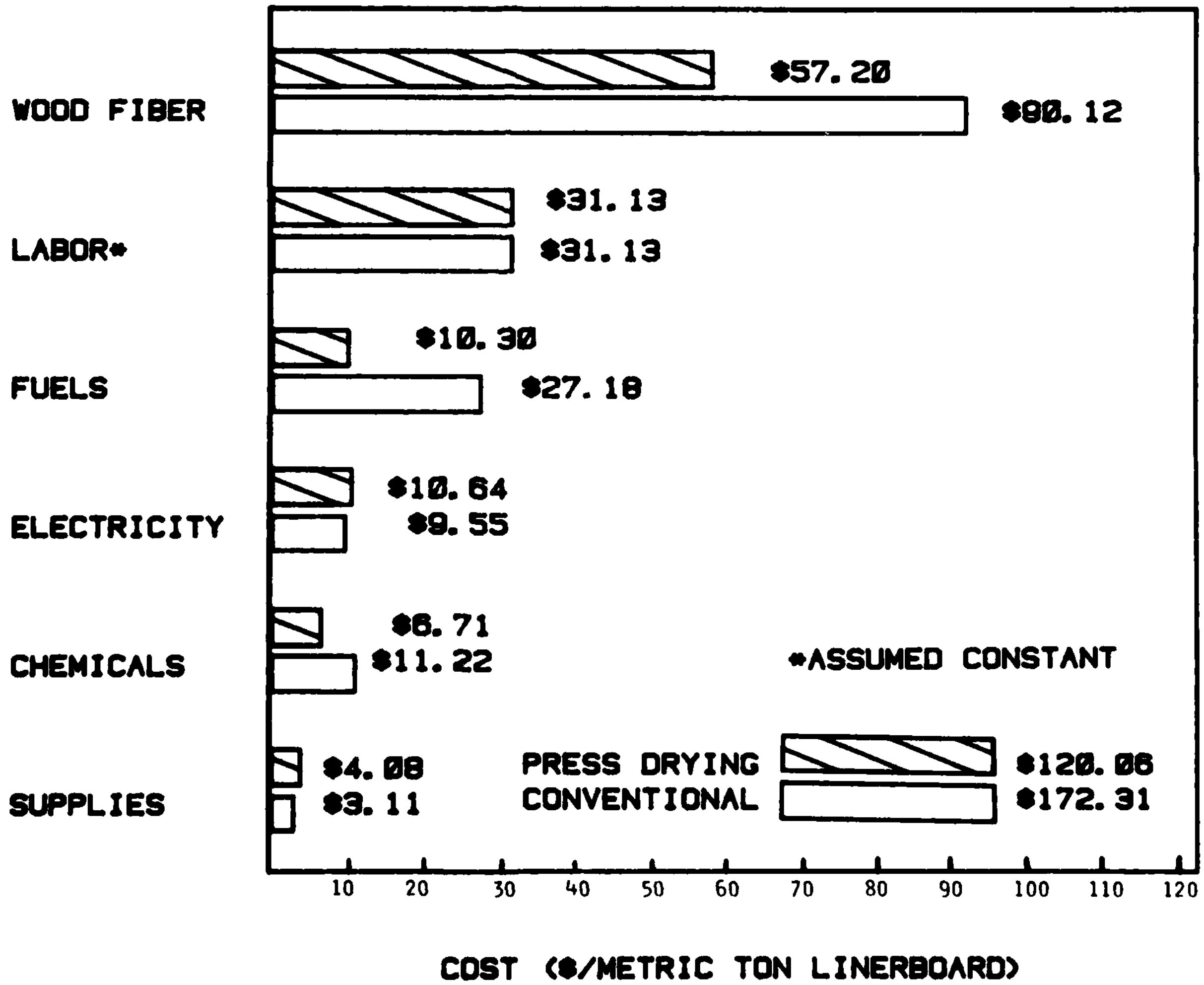

Figure 1.--Variable cost estimates for press-drying and conventional linerboard processes at a new mill. (ML83 5416)

Table 3.--Estimated material requirements for new conventional and press drying linerboard processs

Item	Conventional	Press drying	Item	Conventional	Press drying
Pulpwood raw material (metric tons/metric ton of linerboard, dry weight)	2.074	1.745	Natural gas fuel, for lime kiln (meter^3/metric ton of linerboard)	48.7	30.4
Wood into digester	1.838	1.525	Makeup lime (kilograms/metric ton of linerboard)	9.3	5.8
Bark and fines to power boiler	.236	.220			
Purchased wood fuel (metric tons/metric ton of linerboard)	.424	.227	Purchased saltcake (kilograms/ metric ton of linerboard)	2.7	11.1
Coal fuel (metric tons as purchased/metric ton of linerboard)	.114	--	Caustic soda, for desulfurizing kilograms/metric ton of linerboard)	15.3	5.9

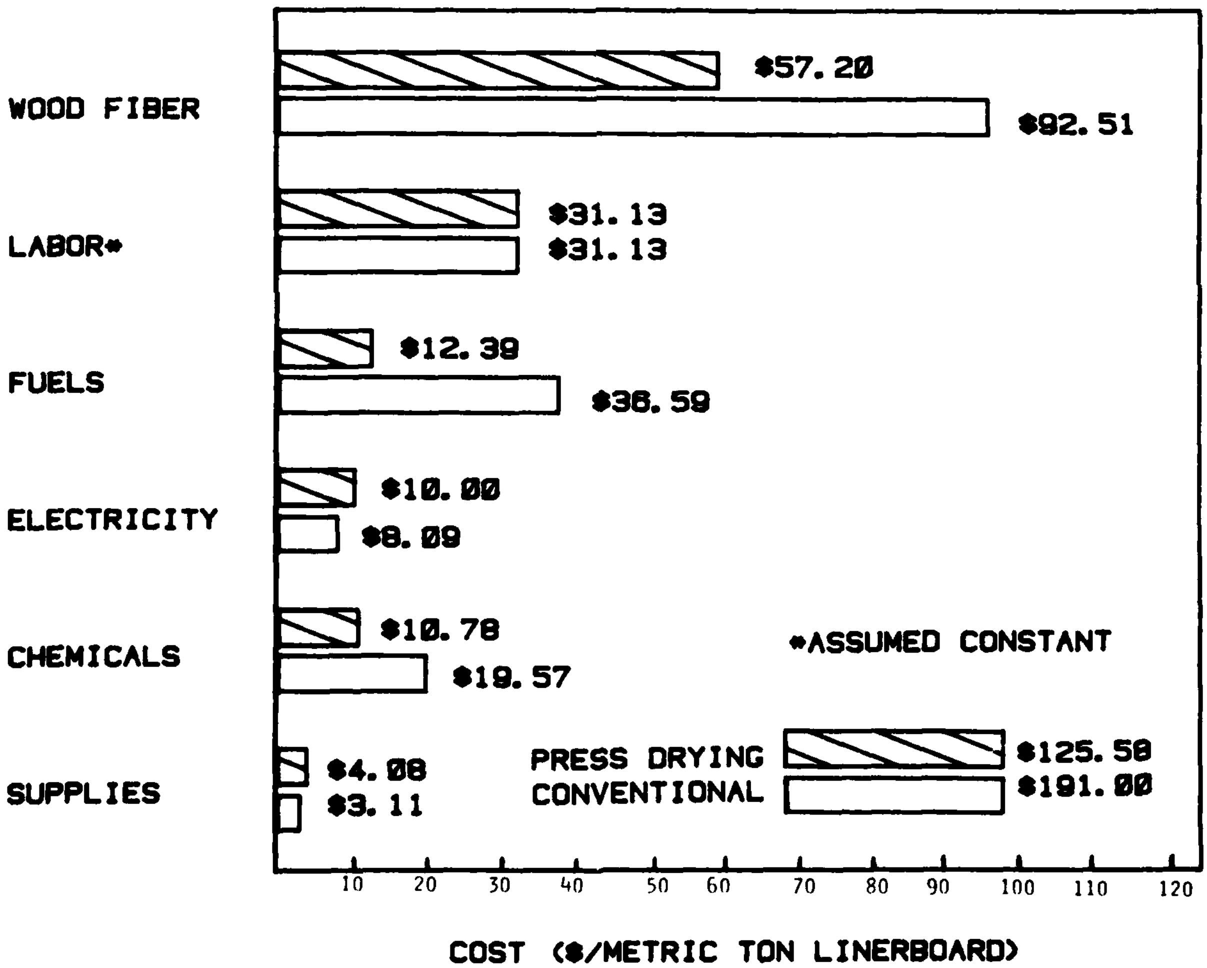

Figure 2.--Variable cost estimates for press-drying and conventional linerboard processes at an older existing mill. (ML83 5417)

Table 4.--Product output and material input value assumptions

Item	Value	Item	Value
Linerboard product (dollars/metric ton, dry weight)	320	Purchased electric power (dollars/ kilowatt hour)	.031
Turpentine product (dollars/liter)	.16	Power boiler auxiliary fuel, coal (dollars/metric ton)	76
Tall oil soap product (dollars/kilogram)	.075	Lime kiln fuel, natural gas (dollars/ meter^3)	.141
Softwood roundwood raw material (dollars/meter^3)	24.30	Alum (dollars/metric ton)	140
Hardwood roundwood raw material (dollars/meter^3)	15.90	Caustic soda, 50% (dollars/metric ton)	420
Softwood chip raw material (dollars/ metric ton, dry weight)	46.30	Rosin (dollars/metric ton)	640
Hardwood chip raw material (dollars/ metric ton, dry weight)	39.70	Defoamer and slimicide additives (dollars/ metric ton)	950
		Sulfuric acid (dollars/metric ton)	82

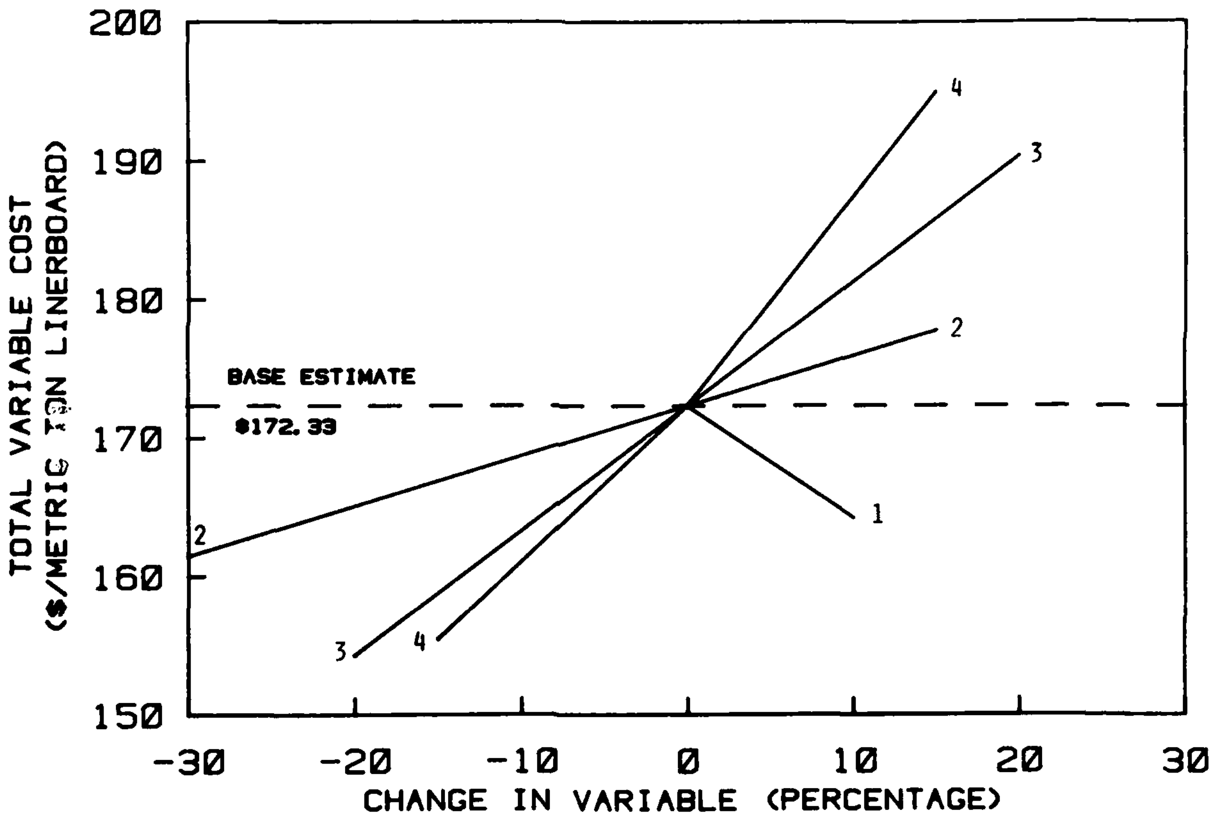

Figure 3.--Sensitivity of total estimated variable cost to percentage change in key variable assumptions for a conventional linerboard process at a new mill.
Variable code:
1 = pulp yield (base level = 53.5%),
2 = percent softwood in fiber furnish (base level = 85%),
3 = value of pulpwood raw material (base level = 100% = $43.50 per metric ton of pulpwood on average),
4 = total process energy requirements (base level = 100% = 24.6 gigajoules per metric ton of linerboard).
(ML83 5418)

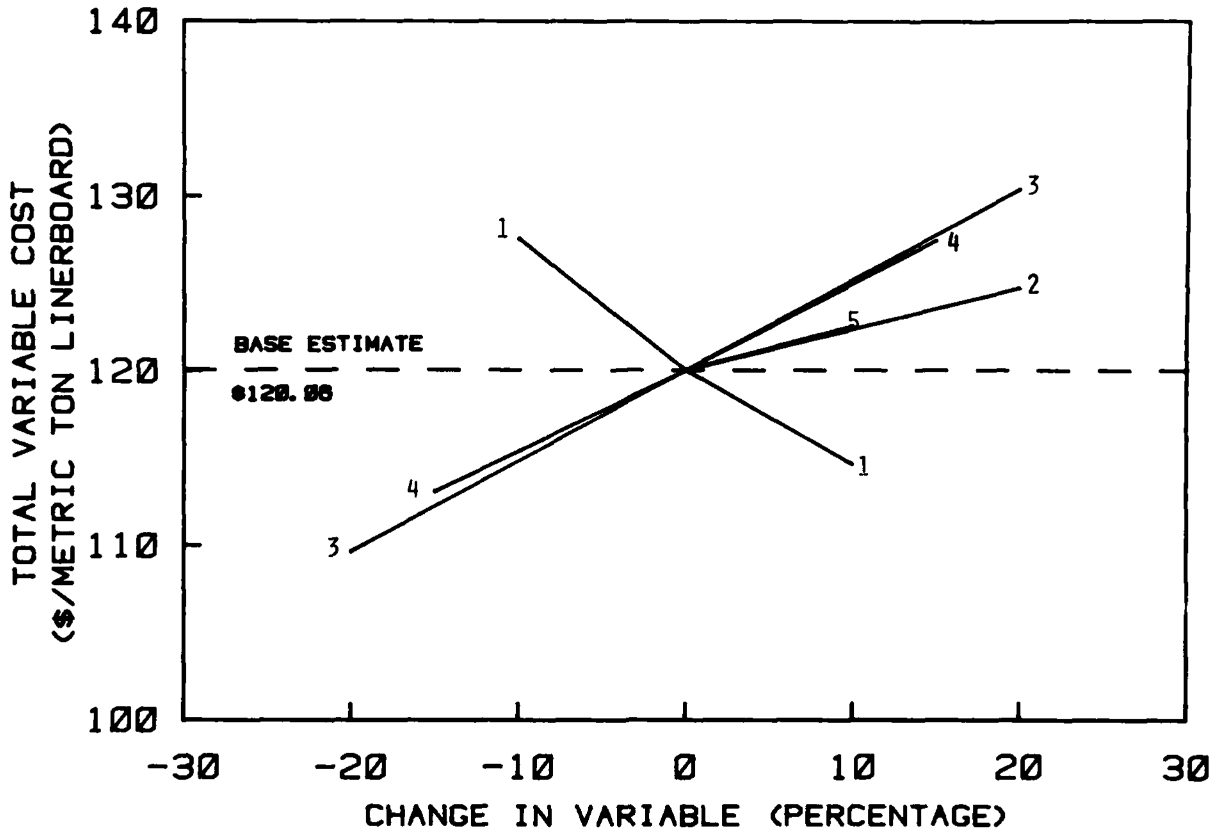

Figure 4.--Sensitivity of total estimated variable cost to percentage change in key variable assumptions for press-drying linerboard process at a new mill.
Variable code:
1 = pulp yield (base level = 65%),
2 = percent softwood in fiber furnish (base level = 0%),
3 = value of pulpwood raw material (base level = 100% = $32.80 per metric ton of pulpwood on average),
4 = total process energy requirements (base level = 100% = 14.9 gigajoules per metric ton of linerboard),
5 = moisture content of sheet as it enters the dryer (base level = 45%). (ML83 5419)

Acknowledgments

The Press Dry Conference Steering Committee consisted of the following FPL personnel: Larry Anderson, John Koning, Jr., Rod Larson, Richard Lindeborg, Gary Lindell, Vance Setterholm, and Robert Steidemann.

The following FPL employees assisted with the conference: Registration and arrangements--Judy Blaser, Sue Howards, and Eleanor Pape; coffee and lunches--Beverly Crapp, Jane Kohlman, Mary Douros, and Judy Blaser; banquet program--Dennis Gunderson; and nametags--John Hunt.

Preparing this volume of extended abstracts prior to Press Dry Conference 1983 required rapid processing of the material at all stages, both at the Forest Products Laboratory (FPL) and at the other institutions that sent speakers to the conference.

Richard Lindeborg, Chief Editor at FPL, coordinated production of the volume and edited all papers written by FPL authors.

William Ireland of the FPL Publications Section coordinated printing of all conference materials. John Bennin of the FPL Copy Center duplicated the papers.

JoAnn Benisch, Steven Schmieding, and James Vargo of the FPL Photo-Graphics Section provided graphics services for all conference materials.

Paul Wright of the FPL Research Facilities Engineering Group coordinated drafting of figures for papers written by FPL authors.

Phyllis Gasner of the FPL Information Processing Center (IPC) coordinated the word processing of papers written by FPL authors. Formatting was done by Ilse Seeliger, Virginia Grabel, and Debra Campbell of IPC.

Papers written by FPL authors were proofread by Karen Nelson and Arvella Thubauville of IPC and by Lenny Dyer of the FPL Publications Section.

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